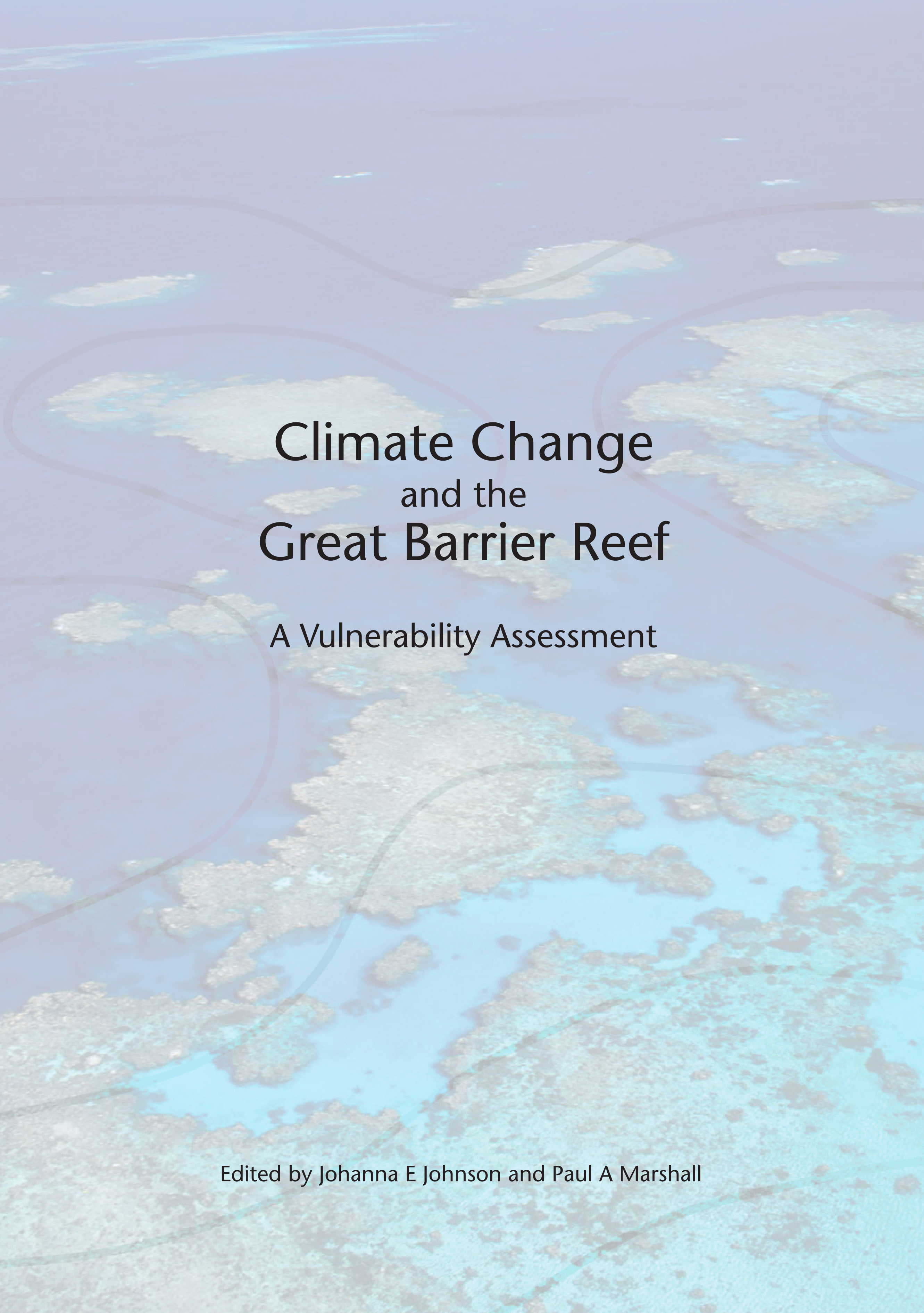

# Climate Change
# and the
# Great Barrier Reef

## A Vulnerability Assessment

Edited by Johanna E Johnson and Paul A Marshall

This publication has been made possible in part by funding from the Australian Greenhouse Office, in the Department of the Environment and Water Resources.

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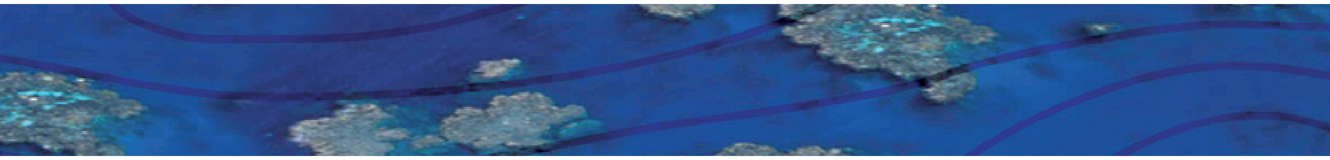

# Climate Change and the Great Barrier Reef

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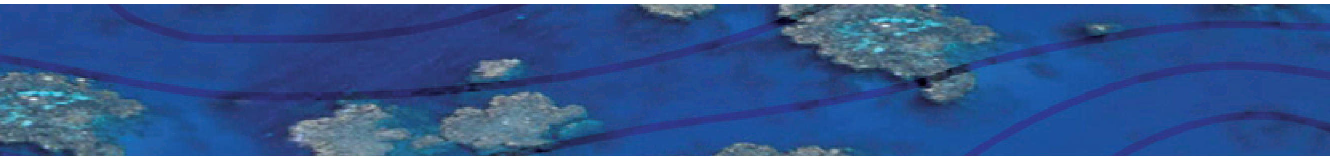


# Foreword

The Great Barrier Reef is one of the truly majestic places on our planet. Its size and brilliance make is observable even from space. Few ocean areas are known as well globally as the 2,300 km of reefs that extend over the Australian east coast.

Comprised of more than 2,900 individual reefs that form its foundation, the Great Barrier Reef World Heritage Area encompasses a diversity of habitats, plants and animals of outstanding universal value. Scattered throughout its footprint are islands, mangroves and marine life of infinite variety. Like the Galapagos, the Great Barrier Reef has singular characteristics found nowhere else on Earth.

But, all of this is under threat as never before.

Global climate change is a virtual sword of Damocles hanging over the very heart of the Great Barrier Reef. History reveals that reefs have been faced with changes in the past, including fluctuations in water temperature, sea level and acidification. Climate change has accelerated this rate of change, coinciding with mounting pressure from human uses. These threats are certainly not unique to the Great Barrier Reef. Around the world, coral reefs are faced with impacts from poor water quality, overfishing, physical damage and climate change. Experts estimate that 20 percent of the world's coral reefs have been effectively destroyed and show no prospect of recovery, another 24 percent are under imminent risk of collapse through human pressures and 26 percent more are under longer-term threat. What makes the Great Barrier Reef unique is that, so far, it has remained in relatively good condition compared to other reefs around the world.

The timing of this book is critical. There is consensus amongst climate experts about the severity of climate change and its link to greenhouse gas emissions. We are now more certain about the amount of change that we can expect and its velocity. Take coral bleaching as an example. In 1998, we saw the world's first recorded global coral bleaching event. Many coral reefs were devastated by rises in sea temperature that exceeded the thresholds that can be tolerated by corals. Since then, worldwide coral reefs have continued to experience coral bleaching and the frequency and potentially irreversible impacts of these events is increasing.

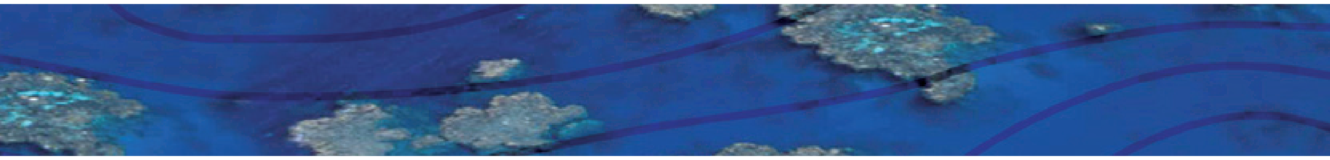
Climate change poses an enormous danger and a new challenge for the protection of our natural heritage. What can marine managers do about changes that are worldwide in scope? We must start with understanding what the impacts on tropical marine ecosystems could be. Identifying the most sensitive species and habitats is an important outcome of this book. Identifying impacts that the ecosystem cannot tolerate is another. Efforts can then be targeted towards protecting these areas.

Unbiased experts are the key to finding solutions. This peer-reviewed book has been prepared by leading tropical marine and climate scientists. As we proceed down the inevitable path of climate change, the idea of change will and has become fundamental to understanding our environment and its role in shaping our ecosystems. Students today will emerge into a world of research and decision-making that did not exist for their predecessors. The authors of this book have provided the first text to assess the role of climate change on an ecosystem as large and diverse as the Great Barrier Reef.

As we experience climate change, we are starting to see real action to reduce greenhouse gas emissions. Governments and industries from around the world are accepting the reality of climate change and are building strategies to reduce their carbon footprint. These efforts must continue. We are committed to some change and we must prepare for it. But efforts to reduce greenhouse gas emissions and the extent of climate change is in our hands.

Based on solid facts, we must work together to find solutions. For without solutions, the Great Barrier Reef and all life is in peril.

**Jean-Michel Cousteau**
Founder and President, Ocean Futures Society



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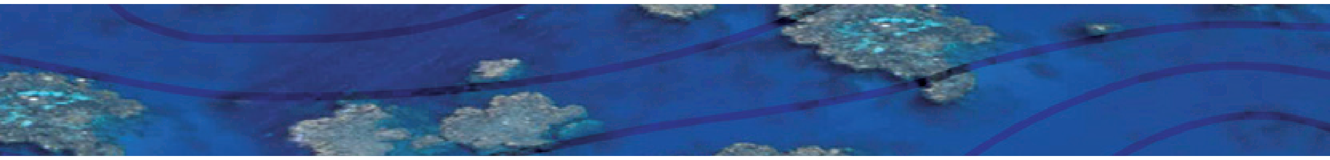

# Preface

In many ways, the expert knowledge compiled in this book confirms what we already know: that the Great Barrier Reef is highly vulnerable to climate change. However, this unprecedented synthesis of current and emerging knowledge takes our understanding to a new level. In doing so, it increases our concern about the future but also gives us cause for optimism.

We now have a much deeper understanding about the extent and range of climate sensitivities that exist within the GBR ecosystem and, significantly, about the gaps in our knowledge. This heightened awareness increases our concern about the fate of corals – which build and maintain the foundations of the GBR – while also bringing into focus the vulnerabilities of many other components of the ecosystem. Although the size of the GBR and the effective long-term management regime afford it some protection from climate change compared to other tropical marine ecosystems, this assessment makes it clear that further degradation is unavoidable. However, there is much scope for minimising the negative impacts of climate change, and for avoiding the worst of their consequences.

The new opportunities for meaningful responses to climate change provide the basis for our optimism. This assessment identifies specific strategies for reducing the vulnerability of particularly sensitive species and habitats, while also refining our knowledge about ways to further restore and maintain the resilience of the ecosystem. While reductions in the rate and extent of climate change remain the single most important goal if we are to improve the prognosis for tropical marine ecosystems, actions to build the resilience of the GBR will be instrumental in averting what leading scientists have called the "coral reef crisis". Effective management of the GBR has never been more important.

This assessment was commissioned by the Great Barrier Reef Marine Park Authority, in partnership with the Australian Greenhouse Office, to comprehensively assess current knowledge about climate change vulnerability, and to identify strategies for building resilience. These insights provide the foundations for the GBR Climate Change Action Plan, which will help GBRMPA and its partners navigate toward a healthy GBR that is more resilient to climate change. We hope that it will be of value to our international colleagues who share the responsibility of protecting tropical marine ecosystems for their beauty, their productivity, and for future generations.

Virginia Chadwick

**Hon Virginia Chadwick**
Chair, Great Barrier Reef Marine Park Authority

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We are grateful to the vast array of climate and tropical marine experts from a diversity of institutes and disciplines who have so willingly contributed to this publication. We appreciate the effort required by authors in tackling such a daunting assessment and the time taken away from core research. We would also like to thank the vast number of nationally and internationally recognised experts who reviewed chapters and shared their thoughts and experiences with us in the compilation of this book.

Many others have played less obvious, but equally important roles. In particular, we wish to acknowledge Catherine Collier for her conceptual diagram expertise, image sourcing and enthusiastic assistance with compiling this publication, and Jeff Maynard and Michelle Heupel for their technical assistance and covering the extra group workload.

Development of this publication would not have been possible without the support of many groups and individuals. Within the Great Barrier Reef Marine Park Authority, senior management provided input to ensure this book was highly relevant to marine protected area management. We particularly acknowledge the leadership and support given by Virginia Chadwick, Andrew Skeat and David Wachenfeld. We are also grateful to Sara Trenerry, Brian Dare, Jo McIntosh, Katie Munkres, Suzie Davies and Julie Jones for their assistance with the production of this book.

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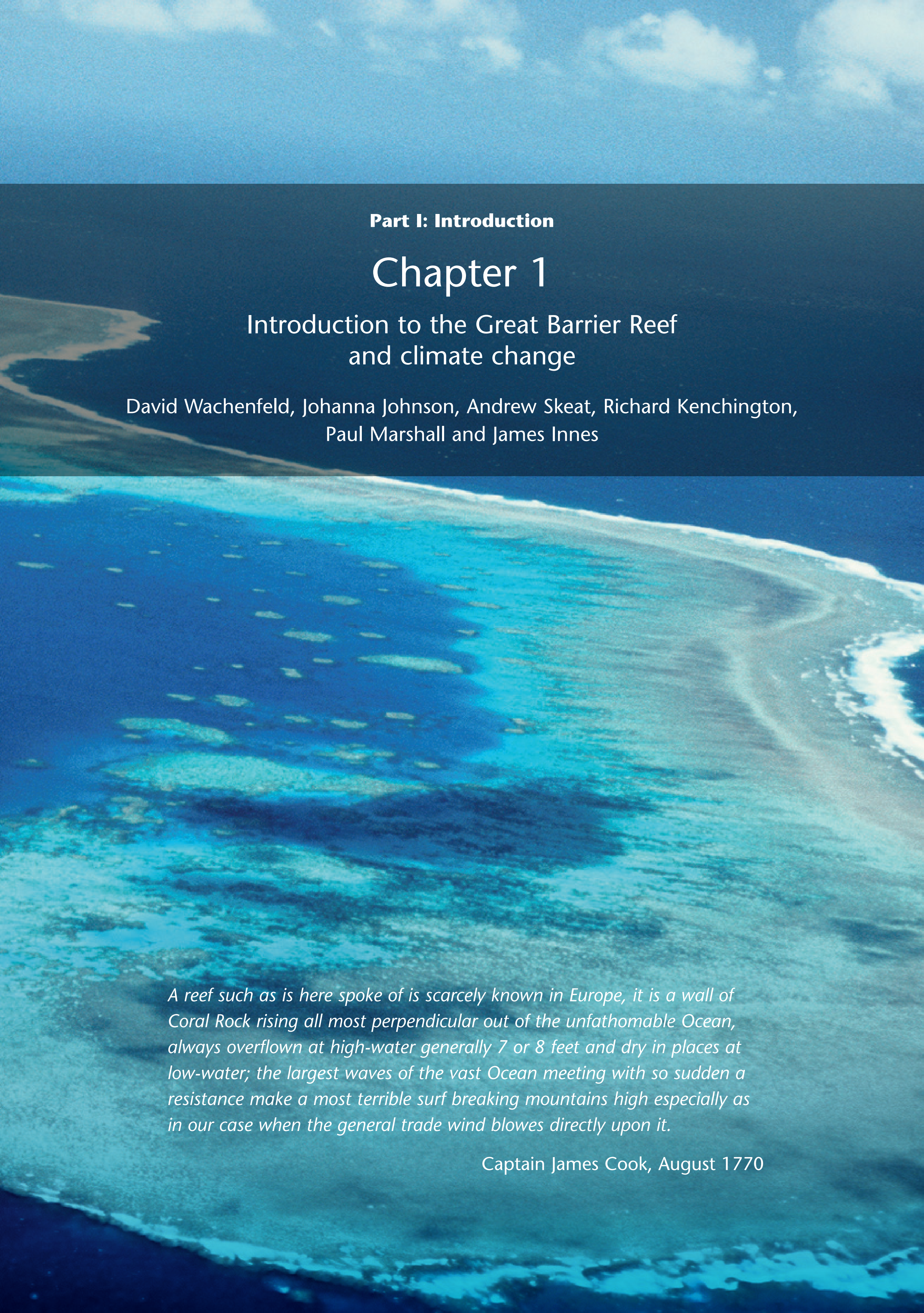


**Part I: Introduction**

# Chapter 1

## Introduction to the Great Barrier Reef and climate change

David Wachenfeld, Johanna Johnson, Andrew Skeat, Richard Kenchington,
Paul Marshall and James Innes

> *A reef such as is here spoke of is scarcely known in Europe, it is a wall of Coral Rock rising all most perpendicular out of the unfathomable Ocean, always overflown at high-water generally 7 or 8 feet and dry in places at low-water; the largest waves of the vast Ocean meeting with so sudden a resistance make a most terrible surf breaking mountains high especially as in our case when the general trade wind blowes directly upon it.*
>
> Captain James Cook, August 1770

## 1.1 Why do a vulnerability assessment?

The Great Barrier Reef owes its genesis to a change in climate approximately twelve thousand years ago. As the last ice age ended, glaciers melted and sea level started to rise and stabilised at present levels about six thousand years ago, which is when the reef formed. It may seem ironic then, that climate change is now regarded as the single biggest threat to the future of the Great Barrier Reef. Yet, human influences on the global climate system are causing changes that have not been seen for hundreds of thousands of years, at a pace that is likely to exceed anything experienced for many millions of years.

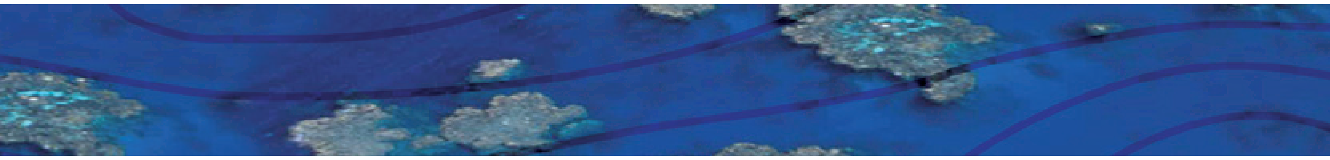
Worldwide, landscapes and ecological systems, together with the social and economic structures that depend on them, are facing a new challenge that is truly global in scale. While few systems are likely to benefit from climate change, coral reefs are particularly vulnerable. Mass coral bleaching events, resulting when sea temperatures become unusually hot, have already caused serious damage to over 16 percent of the world's coral reefs[22]. Although the Great Barrier Reef has not suffered the levels of damage seen in many other regions, up to 5 percent of reefs were severely degraded in each of the 1998 and 2002 bleaching events. Projections of future sea temperatures suggest that coral bleaching could become an annual phenomenon in the course of this century, threatening to undermine the physical and ecological foundations of this diverse and productive ecosystem.

While we have been working to understand the implications of increased sea temperatures for corals, other vulnerabilities are also coming to light. Temperature-sensitivities of other species, such as microbes, plankton, fishes, marine turtles and seabirds indicate the potential for impacts throughout the trophic system. Changes to other environmental variables suggest other impacts on species and habitats, possibly more subtle but also less reversible. The implications of ocean acidification for calcifying organisms such as corals and some plankton, for example, could be profound.

As our awareness of the immediacy and significance of climate change has increased, so, too, has our need to understand the threat. Knowledge of the vulnerability of the Great Barrier Reef to climate change is essential to inform and underpin actions to meaningfully respond to this challenge. While climate change cannot be fully averted, there is much that can, and must, be done to reduce its impacts and to prepare for the changes that are inevitable. This book was conceived to provide the scientific basis for an informed, targeted and effective plan of action to mitigate and adapt to the effects of climate change. While its focus is on the Great Barrier Reef, it is designed to be of interest and value to all who seek to understand the vulnerability of typical marine ecosystems to climate change, wherever they are.

## 1.2 Introducing the Great Barrier Reef

The Great Barrier Reef is renowned internationally for its ecological importance and the beauty of its seascapes and landscapes. These natural values also provide important ecosystem services, which underpin Australian $6.9 billion worth of economic activity[1] and incalculable social values. In combination, the social-ecological system centred on the reef is extraordinary in its importance, and in its complexity. Understanding the vulnerability of such a large and intricate system to climate change is a particularly difficult challenge. A first step in meeting this challenge is to describe the general characteristics of the system and the environment in which they interact. Toward this end, this chapter introduces the Great Barrier Reef and the human systems that interact with it, providing a context for the detailed chapters that follow.



### 1.2.1 The ecosystem

The Great Barrier Reef Marine Park is almost 350,000 square kilometres in area. This makes it larger than the combined area of the Australian states of Victoria and Tasmania. It is also larger than the United Kingdom, Malaysia and many other countries. It spans 14 degrees of latitude and is located along 2100 kilometres of the coastline of Queensland in northeast Australia.

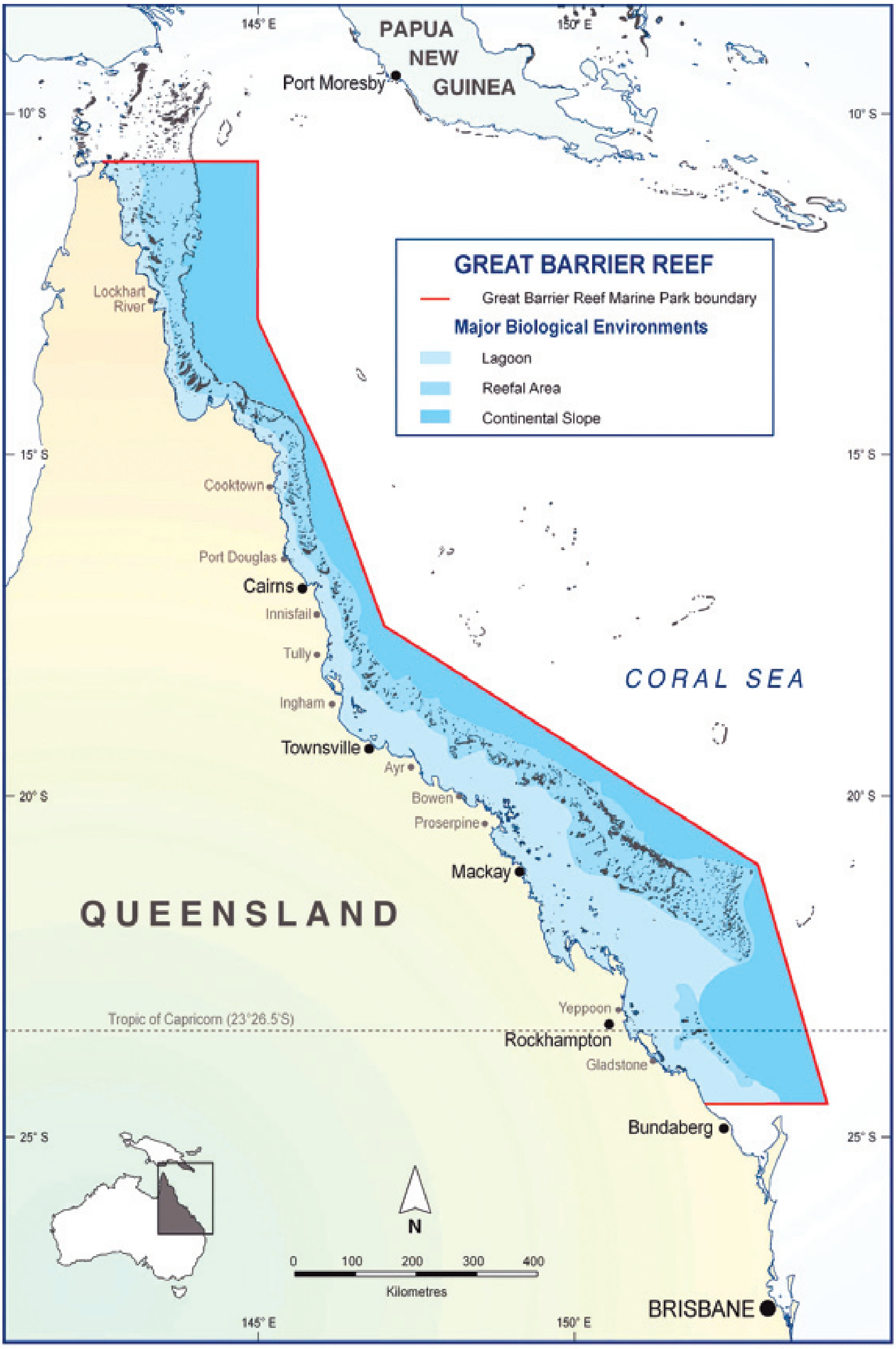
Most people think of the Great Barrier Reef as an enormous single coral reef. In truth, there is a complex maze of about 2900 separate coral reefs. However, these reefs account for only about 6 percent of the area of the Great Barrier Reef Marine Park. About 36 percent of the Great Barrier Reef Marine Park is continental slope, where the water is between 150 and 2000 metres deep. The remaining 64 percent is continental shelf, including the coral reefs, which is anywhere from 1 to 150 metres deep. The other main geographical components of the continental shelf are the inter-reef areas (25% of the Marine Park) and the lagoon (33%). The vast majority of the coral reefs are found relatively far offshore with the inshore lagoon having few reefs (Figure 1.1).

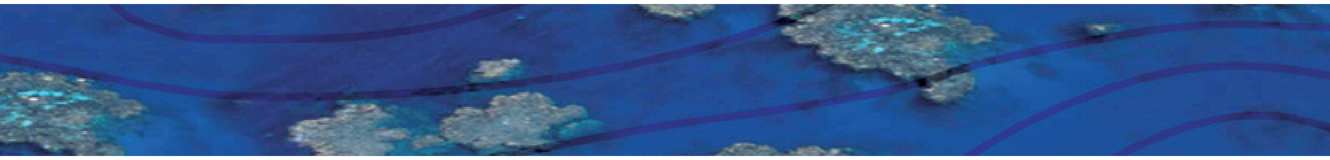
Within these major geographic divisions of the Great Barrier Reef are many different types of habitat and biological community. The best known of these are the coral reefs, but there are also seagrass beds, algal meadows, sponge and soft coral gardens, sandy and muddy areas, mangrove forests and islands. This array of habitats supports an amazing biodiversity. The Great Barrier Reef is home to about 1500 species of fish, 350 species of hard coral, more than 4000 species of mollusc, 500 species of algae, 6 of the world's 7 species of marine turtle, 24 species of seabird, more than 30 species of whale and dolphin and the dugong. And these are just the species that have been recorded so far. As biodiversity surveys continue, more species new to the Great Barrier Reef and sometimes even new to science are being discovered.

The Great Barrier Reef is often heralded as one of the world's best-studied tropical marine ecosystems. Indeed, the coral reefs have been intensively studied since the first formal scientific expedition to the Great Barrier Reef in 1928. Despite this, our understanding of even coral reefs is incomplete. This is unsurprising given that the 2900 coral reefs cover 21,000 square kilometres and are spread out through much of the Great Barrier Reef. Moreover, our understanding of the other major components of the Great Barrier Reef is even less developed. Recent research has begun to unlock the secrets of the inter-reef and lagoon areas by documenting and mapping their biodiversity. However, the continental slope remains an almost complete mystery. In 1990 a trawler brought up a species of crayfish from the continental slope that had never before been encountered in Australian waters. The continental slope is up to 2000 metres deep, presenting a logistical challenge that has discouraged serious research in the area.

Despite a great deal of research, the Great Barrier Reef ecosystem and its biodiversity are far from fully understood. We do not have a complete inventory of the species in the Great Barrier Reef, let alone maps of species distributions or complete accounts of their ecology. Nevertheless there is a great deal that is known and this book draws on that knowledge to assess the vulnerability of Great Barrier Reef species, habitats and processes to climate change.

*Figure 1.1* Major biological environments of the Great Barrier Reef





### 1.2.2 The physical environment

The Great Barrier Reef extends along approximately 14 degrees of latitude, with marine realms spanning coastal to oceanic. This geographic diversity encompasses a range of physical conditions, including various regimes of temperature, current influence, water quality and weather.

The climate of the Great Barrier Reef is influenced by monsoonal wind and rainfall patterns. Strong south-easterly winds dominate during the dry season (April to October), while weaker variable winds are more common during the summer wet season when most of the annual rainfall occurs. Mean sea temperatures in offshore waters vary between 23°C in the coldest months of the dry season (July to August) and 28°C in the warmest months of the wet season (January to February). Inshore areas generally experience a higher seasonal range of between 21 and 30°C. Cyclones are most likely to occur between January and April. The high winds at the centre of a cyclone create large, powerful waves that can greatly affect coral reefs and other marine habitats. Any single cyclone only affects a small proportion of the area of the Great Barrier Reef, but over many decades, almost every part of the Great Barrier Reef will be affected by a cyclone at least once.

Currents are important physical driving factors that strongly affect the Great Barrier Reef's biodiversity and its ecosystem functions. There are three types of current: oceanic, wind-driven and tidal. All three interact in complex ways with the physical structure of the Great Barrier Reef's seabed to produce the current regime. The South Equatorial Current is an oceanic current that flows westward across the Pacific Ocean and Coral Sea. When it reaches the Australian continental shelf at about 14 degrees south, it divides into two currents. One of these flows north along the edge of the continental shelf, the Hiri Current, and the other flows south, the East Australian Current.

At a regional scale, these three currents are the most significant currents that influence the oceanography of the Great Barrier Reef. In some areas, these shelf-edge currents can cause upwelling of deep, cold, nutrient-rich water onto the continental shelf. This upwelled water has regional effects on biodiversity and can cause the formation of significant habitats, such as large algal mounds, only found in the far northern Great Barrier Reef. While oceanic currents have a strong influence on currents on the continental shelf, in shallow waters, currents are also driven by wind. In strong wind conditions, particularly those during the dry season with steady south-easterly winds, the effect of wind on current direction can be stronger than that of oceanic currents. Oceanic and wind-driven currents primarily drive water parallel to the coast, along the continental shelf. However, the tides, which operate on a 12-hour cycle, drive water across the continental shelf perpendicular to the coast. These two driving forces for currents, operating at 90 degrees to each other, create a complex pattern of water movement, especially in and around the intricate matrix of the coral reefs.

### 1.2.3 The human dimensions

The Great Barrier Reef is iconic. It has a central place in Australian culture and psyche, and a visit to the reef is reliably rated among the top three *must do* experiences in international surveys. The Great Barrier Reef has continued to evoke wonder and awe in visitors, from the earliest European explorers negotiating the *"monstrous labyrinth of coral"* by sailing ship, to the thousands of tourists who arrive annually to experience one of the natural wonders of the world. Long before these relatively recent visitors, however, it was Indigenous Australians who had established a strong relationship with the Great Barrier Reef.

Human associations with the Great Barrier Reef predate recorded history. Australia's Aboriginal people knew of and used the reef. Oral history and archaeological evidence shows that they regularly journeyed to the reef to make use of its rich and varied resources[11,20,3,13]. What the region meant spiritually and socially to these people can only be assumed from either early ethnographic accounts[18,20], or interpreted from contemporary reports of association and connection[7,16]. Statements made by contemporary Traditional Owners[23] can also assist understanding.

Aboriginal and Torres Strait Islander people continue to have a strong presence in the Great Barrier Reef. They continually champion their rights and interests in the region[10,6,5] and make use of resources such a fish, dugong and turtle. The majority of Aboriginal and Torres Strait Islander people organise themselves into Traditional Owner groups based on clan and language groups. This form of Traditional Ownership for specific sea country and adjacent lands is an effect of the recognition by the High Court of Australia of the existence of Native Title in the 1992 Mabo Case and subsequent passage into statute of the Native Title Act in 1993. The primary form of interaction Aboriginal and Torres Strait Islander people had and continue to have with the Great Barrier Reef is to support a subsistence lifestyle. Activities such as fishing, hunting and experiencing the Great Barrier Reef are critical to maintain cultural values and identity as the Traditional Owners of the region[17].

The earliest European contact with the Great Barrier Reef[a] was the result of expeditions of discovery. These early expeditions discovered the vastness, beauty and danger of the region. In the 18th century, reports by James Cook of the *"monstrous labyrinth of coral"* and the naturalist reports by Joseph Banks brought the existence of this vast reef area to British and European attention. Throughout the 19th century, the search for safe shipping lanes to the east coast of Australia brought survey vessels with naturalists. Since the 1890s, many more explorers came specifically to visit the Great Barrier Reef. The tradition of formal natural history research[9] and amateur naturalist accounts provided by Banfield's *Confessions of a Beachcomber*[2] revealed to the world aspects of the naturally diverse wonder that is Australia's Great Barrier Reef[9,24,19,4,8,21,14].

In 1893, Saville Kent reported on a scientific study of the fishery and natural resource potential of the Great Barrier Reef. The long-term field studies of the Royal Society of London and Great Barrier Reef Committee Expedition to Low Isles in 1927 to 1928 laid the foundation for the development of coral reef science. After the middle of the 20th century the development of field stations, university research programs and research institutes saw rapid growth in coral reef science. This was coupled with growing development on the adjacent coast and growing technological capacity to reach and exploit the Great Barrier Reef. The adventure of the expedition to the reef continues to draw people. The thrill of exploring its varied aspects and enjoying the many forms of nature entrances people and brings them back to the Great Barrier Reef[15].

There are significant social and economic benefits to Australia from the Great Barrier Reef. The major activities that occur on the Great Barrier Reef are tourism, recreation and commercial fishing. During 2005, 1.9 million people visited the Great Barrier Reef using tourism services and it is estimated that

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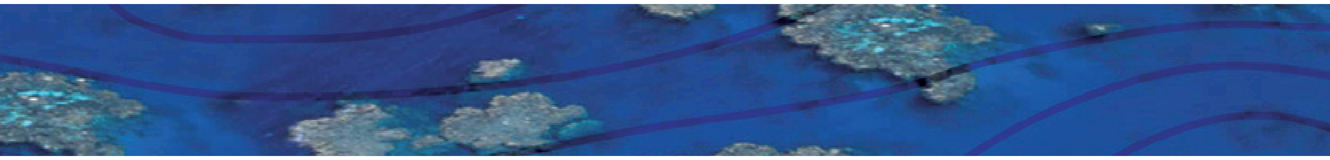
[a] Torres and Prado in 1606, James Cook and the Endeavour in 1770, Matthew Flinders in the *Investigator, Cato* and *Porpoise* in 1801–03, King in the *Mermaid* and *Bathurst* in 1819–21, Stokes, Wickham, Bynoe in the *Beagle* 1839-41, Blackwood Jukes and MacGillivray in the *Fly* in 1843-45 and the *Rattlesnake* in 1847–49, Mosely in the *Challenger* in 1887; Coppinger and Miers in the *Alert* in 1881 and McFarlane in the *Constance* in 1887.



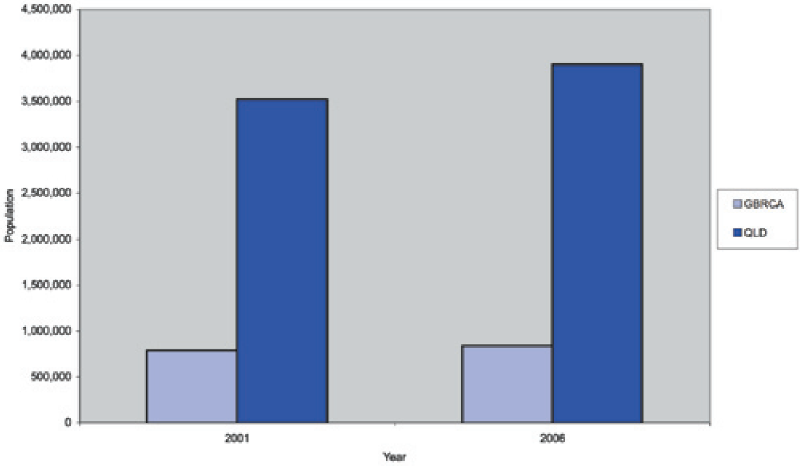
there are a further 6 million recreational visits to the Great Barrier Reef annually. Recreation includes activities such as fishing, snorkelling, diving, sightseeing, adventure sports and sailing. Tourism is a major activity on the Great Barrier Reef and is estimated to contribute as part of regional tourism $6.1 billion to the Australian economy annually[1]. The tourism industry also employs an estimated 63,000 people. Commercial fishing activity undertaken in the Great Barrier Reef has a gross value of production of $119 million annually and employs an estimated 3,600 people or 0.94 percent of the Great Barrier Reef coastal labour force. Recreational fishing and boating contribute $640 million annually to the region and comprise a major recreational activity for residents and visitors to the region.

At the 2006 census, there were approximately 836,000 people living in the Great Barrier Reef Catchment with an average annual growth rate of 1.23 percent. This is 21 percent of Queensland's resident population of almost 4 million (Figure 1.2). The region is economically dependent on agriculture, manufacturing and mining except in Cairns city, Douglas and Whitsunday Shires that have tourism as their major industry. Sugar cane is the main crop grown on the Queensland coast.

The value of agricultural production from Great Barrier Reef coastal communities is in the order of Australian $1.7 billion annually. The resources sector contributes Australian $14.5 billion annually in exports from the 11 ports located in the Great Barrier Reef region[b]. Of these exports, 94 percent are for mineral products, primarily coal and metal ores, and the remaining 6 percent agricultural and manufactured products.

The key regional centres of Cairns, Townsville, Mackay, Rockhampton and Gladstone provide services to inland mining and agricultural industries. Townsville is the largest major centre in the Great Barrier Reef region with considerable government, education and defence activities servicing state and national interests.

***Figure 1.2*** *Residential population in the Great Barrier Reef Catchment Area and Queensland for 2001 and 2006. (Source: Australian Bureau of Statistics 2007)*



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[b] http://www.oesr.qld.gov.au/

Limiting the effects of people, within and adjacent to the Great Barrier Reef is the challenge presented to marine managers, communities, industries and governments when considering how best to manage the Great Barrier Reef. The nature of the interactions people have with the Great Barrier Reef are shaped by the demands they have to meet. For each ecosystem the type of management applied to maintain its functional status, as a 'healthy' ecosystem is directly dependent on the social, economic and institutional context of the society that interacts directly and indirectly with the ecosystem.

The length of time that humans have interacted with the Great Barrier Reef provides an appropriate historical context for understanding current social, economic, institutional and political issues involved in the management of the Great Barrier Reef. Unlike many other tropical marine ecosystems[c], the Great Barrier Reef exists in close proximity to a region that has experienced intensive farming and pastoral activities as well as substantial urban development for close to one hundred and fifty years. Apart from the Cape York region, which has experienced much less land based development; coastal and catchment regions bordering the Great Barrier Reef bear witness to the progressive development of the region's ocean, land and mineral resources.

The infrastructure for supporting the growing regional population of approximately 836,000 people with associated manufacturing, agricultural and urban services from Bundaberg in the south to Cairns in the north represents a substantial modification of the Great Barrier Reef's coastal and catchment landscape. The effect of 68,000 personal watercraft, active commercial fisheries, 1.9 million tourist visits annually, defence activities and development of infrastructure to support visitors and residents accessing and enjoying the Great Barrier Reef combines to make an extensive ecological footprint. This will affect the Great Barrier Reef in far more complex forms than tropical marine ecosystems that are more isolated.

### 1.2.4 Management and conservation

In recognition of its diverse, unique and universal values, the Great Barrier Reef is listed as a World Heritage Area, and protected within the Great Barrier Reef Marine Park. The enactment of the Great Barrier Reef Marine Park Act in 1975 by the Commonwealth established the legal framework for protecting these values for conservation and wise use into the future. Further recognition of the importance of the outstanding universal values of the Great Barrier Reef occurred in 1981 when the area was listed as a World Heritage site.

The Great Barrier Reef Marine Park Act establishes a Great Barrier Reef Marine Park Authority with responsibility for managing the Marine Park. The goal of the Authority is the long-term protection, ecologically sustainable use, understanding and enjoyment of the Marine Park. A range of management tools are used including zoning plans, management plans, site plans, environmental impact assessment, permits and programs providing information, education and compliance. The Marine Park is managed in association with the Queensland Government, which undertakes day-to-day management through several agencies. For example, the Queensland Government is responsible for the management of commercial fisheries in the Marine Park.

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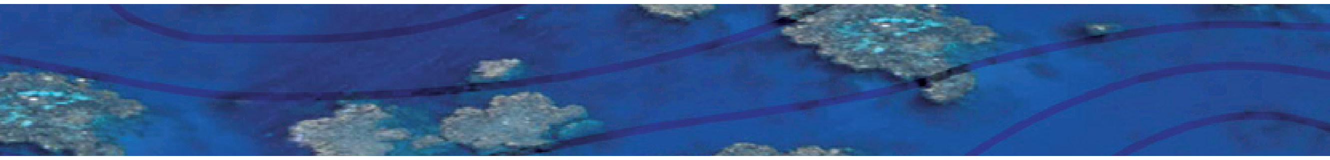
[c] The Florida Keys is another exception as it too lies adjacent to a heavily developed coastal area



Community input into Marine Park management is actively sought through a range of committees including Reef Advisory Committees and Local Marine Advisory Committees, which deal with key issues such as water quality, and 11 Local Marine Advisory Committees.

Despite national and international frameworks designed to conserve the Great Barrier Reef, it is under pressure from a range of local, regional and global stresses. Local and regional issues, such as water quality and fishing, are managed through a range of plans, regulations and agreements. Recent key management actions aimed at increasing the resilience of the Great Barrier Reef include the *Reef Water Quality Protection Plan* and the rezoning of the Marine Park in 2003.

The *Reef Water Quality Protection Plan* is a multi-stakeholder agreement to 'halt and reverse the decline in water quality entering the Reef within ten years'. The *Reef Water Quality Protection Plan* contains nine strategies including education and extension, economic incentives and regulatory changes. Major investment in the *Reef Water Quality Protection Plan* is flowing through programs such as the Natural Heritage Trust. A comprehensive water quality and ecosystem health monitoring program has been put in place under this initiative.

The Marine Park was rezoned in 2003 to increase the level of protection afforded to the Great Barrier Reef. The overall proportion of the Marine Park included in highly protected no-take zones increased from less than 5 percent to more than 33 percent. Most importantly, at least 20 percent of each of 70 bioregions was included in no-take zones. The rezoning is accepted internationally as a world leading initiative with regard to protecting ecosystem health and maximising the resilience of a tropical marine ecosystem.

Considerable management effort is also invested in ensuring ecologically sustainable outcomes for tourism and fishing industries in the Great Barrier Reef. All tourism activity is subject to environmental impact assessment and requires permits to operate. The impacts of fishing are minimised through negotiation between the Great Barrier Reef Marine Park Authority and the Queensland Government with outcomes including management plans for trawling and coral reef line fishing, which include a total allowable catch and spawning closures.

Despite these landmark initiatives, the ecological integrity of the Great Barrier Reef and its ability to sustain provision of goods and services to society are under increasing threat from climate change. While some level of change is inevitable, it is now imperative that action is taken to reduce the magnitude of human related impacts on the Great Barrier Reef ecosystem, and the industries and communities that depend on it.

## 1.3 Understanding vulnerability and uncertainty

Global stresses associated with climate change pose new challenges for natural resource management. Efforts to understand the threat are often hampered by substantial gaps in knowledge about natural systems, as well as by uncertainty in climate scenarios and in ecosystem responses. Approaches and frameworks to assist with assessments of vulnerability and their uncertainty are emerging as efforts to understand the implications of climate change intensify.

The Great Barrier Reef is not immune to the threat of climate change. Climate change, together with other human pressures is having synergistic effects on the Great Barrier Reef. Although environmental managers cannot directly control climate, there is an urgent need to identify possibilities for reducing climate-induced stresses on the Great Barrier Reef ecosystem, and to develop strategies to support natural resilience and adaptation in the face of uncertainty. An important part of this response to the threat of climate change is investigation of the vulnerabilities and risks of climate change effects on all components of the Great Barrier Reef ecosystem.

Climate vulnerability refers to ecosystem's potential to suffer damage or ill effects as a result of climate change. There is an increasing likelihood that climate change will create a need for adjustments of established ecosystems on spatial and temporal scales that are unprecedented in human history. Further, such changes are unplanned with an ever-increasing risk that, as the concentration of greenhouse gases in the atmosphere grows so too does the prospect of irretrievable damage. Vulnerability assessments of ecosystems to climate change provide a structure for examining the potential impacts of climate change and adaptation options.

### 1.3.1 Assessing vulnerability

Vulnerability assessments are a form of integrated assessment that aim to integrate social, ecological and economic information. This technique has been applied extensively in other domains, such as hazard risk and human health, however it is a relatively new method in the climate change arena.

Initiatives in other domains appear to be adopting similar conceptual frameworks, generally deriving from well-developed thinking in climate policy and science. Knowledge of vulnerability is generally derived from an integrated assessment approach that includes scientific information (published and unpublished), professional and community knowledge and expert opinion. Assessments of vulnerability or risk are social processes linking public knowledge to policy and governance frameworks[12].

The Intergovernmental Panel on Climate Change (IPCC) has described climate change vulnerability as: *The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity*[d].

This publication draws on this approach, where the vulnerability of a system to climate change is a function of three elements: exposure (to climate change effects), sensitivity, and adaptive capacity (Figure 1.3).

This approach to assessing of vulnerability is important because it highlights the key elements that combine to amplify (or alleviate) the costs and risks that climate change can impose on a system. Understanding these elements can help identify the climate change threat, highly vulnerable elements and action in each of these areas that can help reduce or deal with that threat.

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[d] IPCC 2001, Third Assessment Report

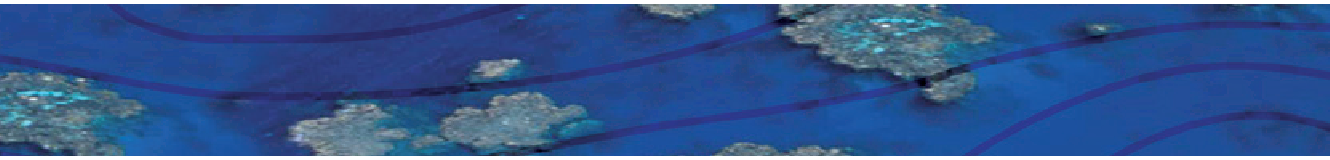
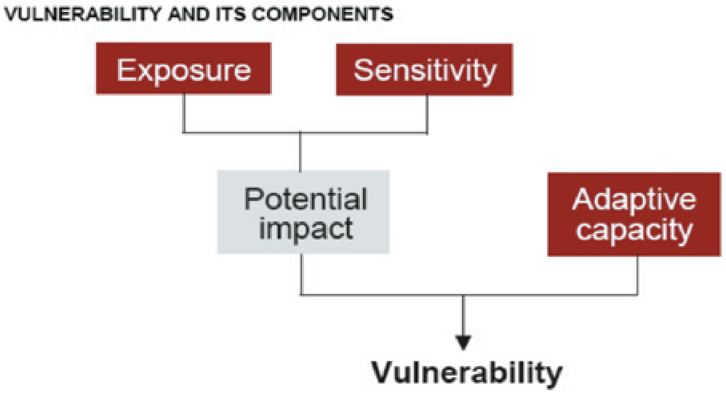


***Figure 1.3*** *Framework for assessing vulnerability of the Great Barrier Reef to climate change*



Source: Adapted from D. Schroter and the ATEAM consortium 2004, *Global change vulnerability — assessing the European human–environment system*, Potsdam Institute for Climate Impact Research.

The success of incorporating the findings of vulnerability assessments into policy depends on whether they are perceived to be salient, credible and legitimate. That is, that stakeholders respect the source of the information, understand the assessment process and have participated in the assessment. This vulnerability assessment engaged expert scientists who integrated all current knowledge to assess the vulnerability of the different components of the ecosystem. The assessment of social vulnerability engaged with communities and industries that depend on the Great Barrier Reef, are regular users of the reef or reside in the reef catchment. In this way, the information used for the assessment was sourced from a representative population that participated in the process.

### 1.3.2 Dealing with uncertainty

Uncertainty, in the context of assessing vulnerability to climate change, comes from a range of sources, such as unpredictability, structural uncertainty and value uncertainty. Unpredictability usually refers to uncertainty about projections of human behaviour, ie how human society will change in the future and the resultant effect on greenhouse gas emissions. Structural uncertainty comes from inadequate or incomplete models, ambiguous system boundaries or definitions, or poorly considered processes or relationships. Value uncertainty comes from missing or inaccurate data, inappropriate spatial or temporal resolution or poorly known or changing model parameters. All forms of uncertainty can be addressed by clearly defining the scope of the assessment, using plausible scenarios, setting specific assumptions and parameters, estimating the degree of uncertainty and the probable range of predictions based on that uncertainty.

Expert judgements are a mechanism for dealing with uncertainty by providing a traceable account of the steps taken to reach key findings, and to estimate uncertainty or confidence in those findings. Where knowledge is extensive, expert judgements will have less uncertainty and greater confidence and will be quantitative in nature. However, a lack of data does not prohibit making expert judgements, and should instead draw on the available information to make judgements on the direction of change, degree of change, expected trend, range of change or threshold or a likelihood or probability of occurrence. This guidance on uncertainty[e] was used by authors when making assessments of the vulnerability of the Great Barrier Reef to climate change.

## 1.4 How to use this book

This publication is intended as a resource for scientists, managers and anyone with an interest in the future of coral reefs. In order to assess the vulnerability of a complex ecosystem such as the Great Barrier Reef, divisions of the ecosystem need to be made. There are many ways to group the various components of the Great Barrier Reef, however, for ease of reading and undertaking effective assessments the following pragmatic organisation has been used. The book has been divided into sections that deal with species and species groups, habitats, processes and management of the Great Barrier Reef.

An **Introductory** section provides background information on the Great Barrier Reef, current and future climate scenarios for the Great Barrier Reef, climate change implications for physical oceanography and the concept of resilience as it relates to the Great Barrier Reef and climate change.

A **Species and Species Group** section assesses the vulnerability of species in the Great Barrier Reef to climate change, from tropical marine microbes and plankton to fish, corals, seagrass and whales.

A **Habitat** section assesses the vulnerability of the major habitats within the Great Barrier Reef to climate change, including coral reefs, pelagic environments, coasts and estuaries and islands and cays. This section also provides an assessment of how climate change will affect the geomorphology of coral reefs, reef islands, beaches and coasts, and a historical perspective of coral reefs and climate change over geological time.

Finally, a **Concluding** section that provides a synthesis of the implications of climate change for Great Barrier Reef communities and industries and a summary of the key vulnerabilities and management implications for the Great Barrier Reef.

Chapters within this book are comprehensive, however, as the Great Barrier Reef ecosystem is interlinked, so too are the chapters that deal with the different components of the ecosystem. Therefore, chapters frequently draw on each other and reference the assessments of other chapters.

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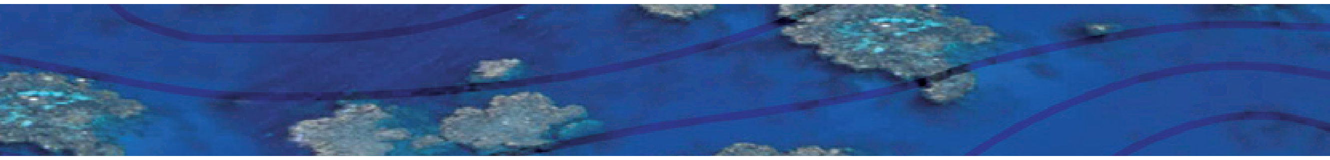
[e] Intergovernmental Panel on Climate Change, Guidance Notes on Uncertainty for Fourth Assessment Report (2005)



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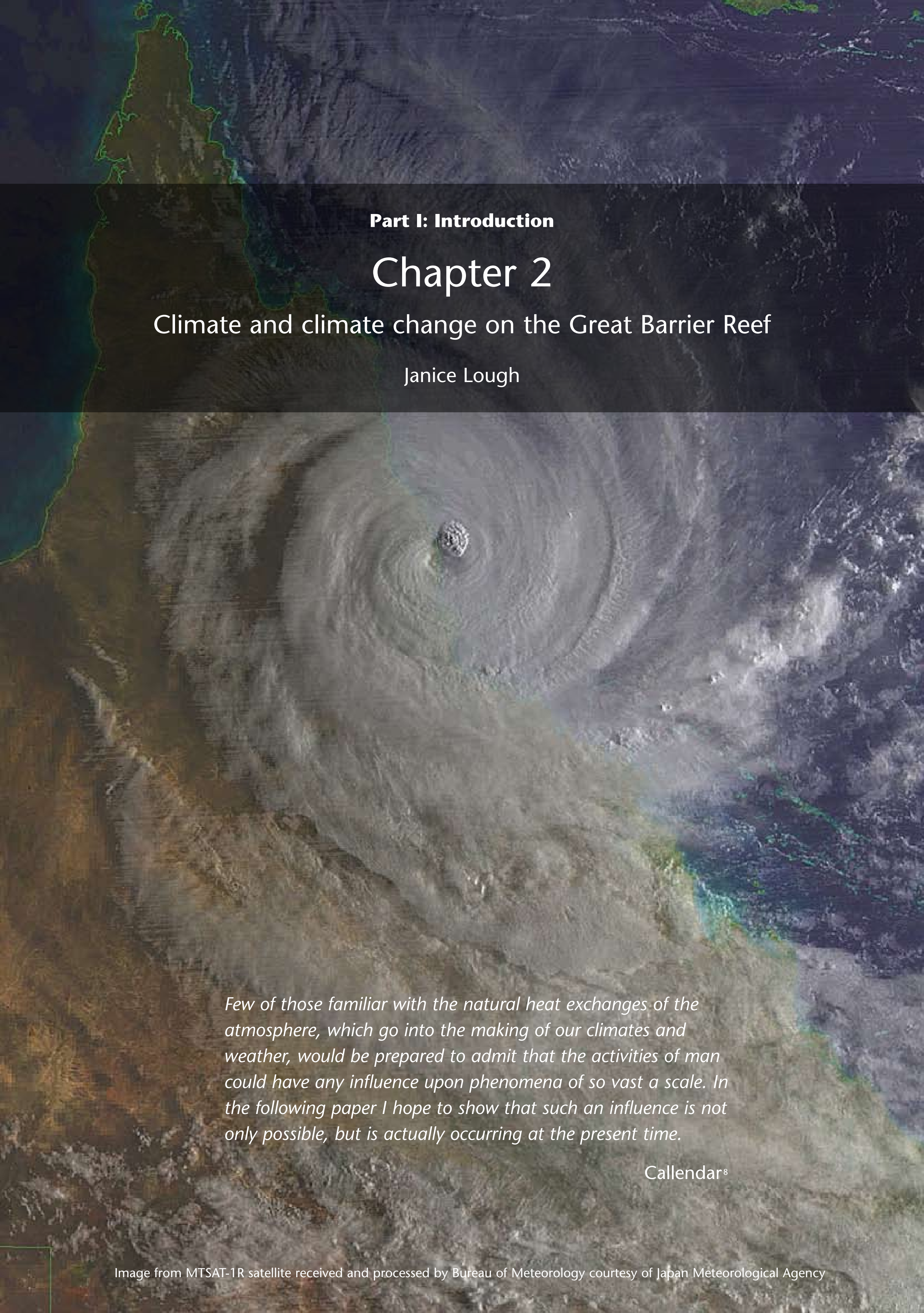


## Part I: Introduction

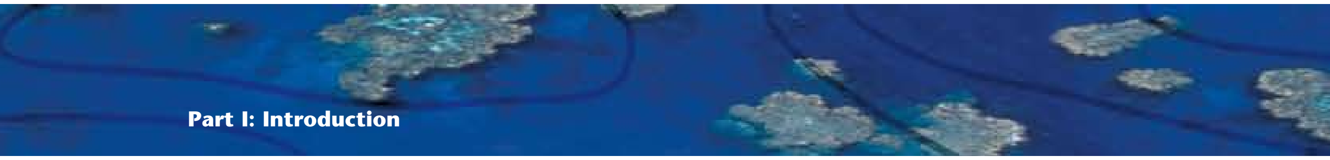
# Chapter 2

## Climate and climate change on the Great Barrier Reef

Janice Lough

> *Few of those familiar with the natural heat exchanges of the atmosphere, which go into the making of our climates and weather, would be prepared to admit that the activities of man could have any influence upon phenomena of so vast a scale. In the following paper I hope to show that such an influence is not only possible, but is actually occurring at the present time.*
>
> Callendar[8]

Image from MTSAT-1R satellite received and processed by Bureau of Meteorology courtesy of Japan Meteorological Agency



## 2.1 Introduction

The expectation of climate change due to the enhanced greenhouse effect is not new. Since Svante Arrhenius in the late 19th century suggested that changing greenhouse gas concentrations in the atmosphere could alter global temperatures[3] and Callendar[8] presented evidence that such changes were already occurring, we have continued conducting a global-scale experiment with our climate system. This experiment, which began with the Industrial Revolution in the mid 18th century, is now having regional consequences for climate and ecosystems worldwide including northeast Australia and the Great Barrier Reef (GBR).

This chapter provides the foundation for assessing the vulnerability of the GBR to global climate change. This chapter outlines the current understanding of climate change science and regional climate conditions, and their observed and projected changes for northeast Australia and the GBR.

## 2.2 A changing climate

*The last five years have seen a rise in observable impacts of climate change, especially those, such as heatwaves that are directly related to temperatures. The impacts of rising temperature on the Earth's biodiversity are also now well documented and there is some circumstantial evidence for an increase in storms, floods and other extreme events as well as in the intensity of tropical cyclones. Adaptation to climate change is no longer a question of* ***if*** *but now of* ***how****,* ***where****, and* ***how fast****.*

Steffen[57]

### 2.2.1 Weather and climate

Weather is the state of the atmosphere at a given time and place as described by variables such as wind speed and direction, air temperature, humidity and rainfall. Climate is what we expect the weather to be like at a particular time of year and place, based on many years of weather observations (30 years has typically been used by the World Meteorological Organization to define climate 'normals')[a]. The climate of a region includes both long-term averages of the various weather elements and their variability about the averages (ie observed range of extremes, standard deviation). Surface climate of northeast Queensland and the GBR is, therefore, defined by what we expect the air temperatures, sea surface temperatures, rainfall, river flow, wind speed and direction, occurrence of tropical cyclones and ocean currents to be like at any given location and season.

### 2.2.2 Climate variability and change

Global climate has varied on a range of time and space scales. For example, climate variations over hundreds of thousands of years between glacial and inter-glacial conditions due to changes in Earth's orbital position[5]; and spatial differences allowing classification of Australian climate zones[59]. Current climate conditions in the vicinity of the GBR were established after the end of the last ice age

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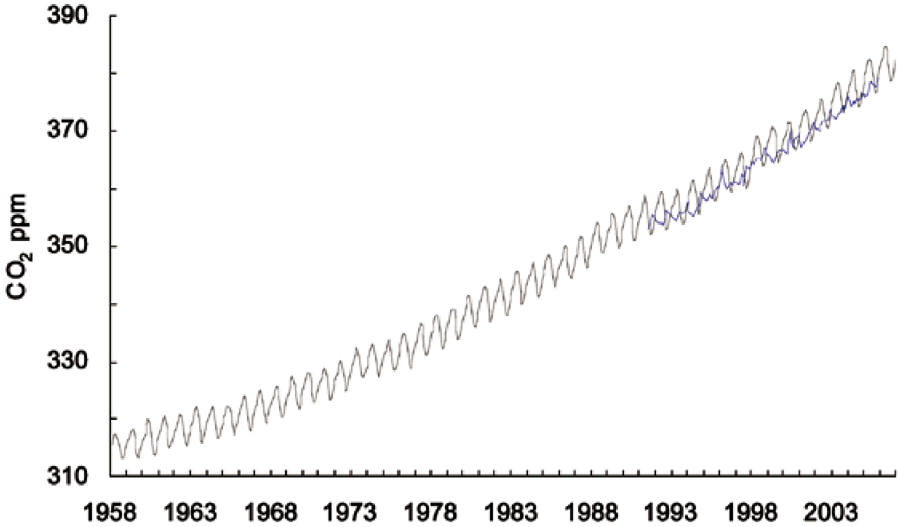
[a] American Meteorological Society

with current sea level being reached about 6000 years ago. Climate varies naturally due to various factors that are internal and external to the complex climate system (consisting of the interacting atmosphere, oceans, biosphere, land surface and cryosphere) including feedbacks that can amplify or dampen an initial disturbance, variations in solar and volcanic activity, but usually within the range of observed average climate and its extremes. A climate change occurs when there is a significant change in average climate and/or its variability with the consequence that our expectation of what the weather will be like also changes.

### 2.2.3 Global climate change

Human activities since the Industrial Revolution in the mid-18th century have increased the atmospheric concentration of greenhouse gases. These gases are present naturally in our atmosphere and without this 'natural' greenhouse effect the Earth would be about 30°C cooler with conditions inhospitable to life, that characterise Mars and Venus. The increased concentration of greenhouse gases (the enhanced greenhouse effect) essentially traps more heat in the global climate system and causes *global warming* (Figure 2.1). There is now no scientific doubt that human activities have changed the composition of the atmosphere and the oceans[24]. The change in the heat balance of the earth is now causing observed changes in global and regional climate[23,24] (Figure 2.2).

***Figure 2.1*** *Monthly atmospheric concentrations of carbon dioxide ($CO_2$) for Mauna Loa, Hawaii (grey, 1958 to 2006) and Cape Ferguson, Queensland, Australia (blue, 1991 to 2005) illustrating the well-mixed nature of this atmospheric gas with local trends matching global trends and the steady increase in atmospheric concentration of the major greenhouse gas attributable to human activities. (Data source: World Data Centre for Greenhouse Gases[b])*



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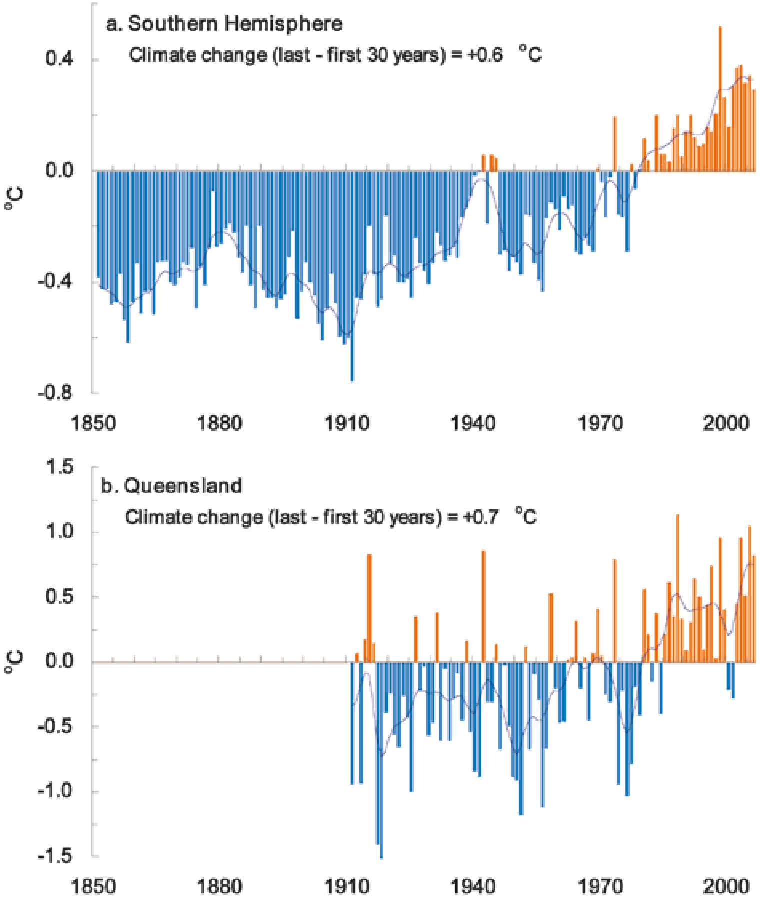
[b] http://gaw.kishou.go.jp/wdcgg.html

***Figure 2.2*** *Instrumental October to September anomalies from 1961 to 1990 mean for a) Southern Hemisphere air and sea temperatures, 1851 to 2006 and b) Queensland air temperatures, 1911 to 2006. Thick line is 10-year Gaussian filter emphasising decadal variability. The two series are significantly correlated, 1911–2006, r = 0.66. (Data sources: HadCRUT3, Climatic Research Unit, UK, Brohan et al.[7]; Australian Bureau of Meteorology, Lough[33])*



## 2.2.4 Future climate change and uncertainty

Projecting the global and regional consequences of the enhanced greenhouse effect is a complex problem. Solving this problem relies on adequate understanding and modelling of past and current climate conditions, the factors responsible for maintaining these conditions and the factors that drive changes in climate. Modelling how climate will change in an enhanced-greenhouse world also depends on projecting how greenhouse gas concentrations will change in the future. This depends on a variety of socio-economic factors such as population growth, levels of affluence, intensity of energy use and the strategies implemented to reduce future emissions (mitigation). Hence, there is no single future climate scenario for a doubling of atmospheric greenhouse gas concentrations, but

rather a range of possible futures that depend on human factors (Appendix 2.1 Special Report on Emissions Scenarios (SRES) storylines[46]), climate sensitivity, responses and feedbacks and the ability of different climate models to faithfully simulate climate[23,65,69]. These plausible projections of future climate conditions contain two major sources of uncertainty. Firstly, uncertainty due to differences between individual climate models because of incomplete understanding of the physical processes of the climate system and how they work together and interact. Secondly, uncertainties due to different assumptions and projections of future greenhouse gas concentrations. Our ability to project and assess the regional consequences of global climate change and, thus locally relevant impacts, depends on our ability to realistically downscale global climate projections. The coarse spatial resolution used in current global climate models does not provide this local-scale weather and climate detail and several (downscaling) techniques are used to provide regional climate information based on the large-scale climate conditions produced by global climate models[71]. Current limitations in local-scale climate projections[69] add therefore, another level of uncertainty (and increases the range of possible future climate conditions) in assessing climate change impacts (Figure 2.3).

Regional projections of temperatures for northeast Australia and the GBR have greater certainty than those for rainfall and river flow. This is because:

1) Regional rainfall may either increase or decrease in future whereas temperature will increase,

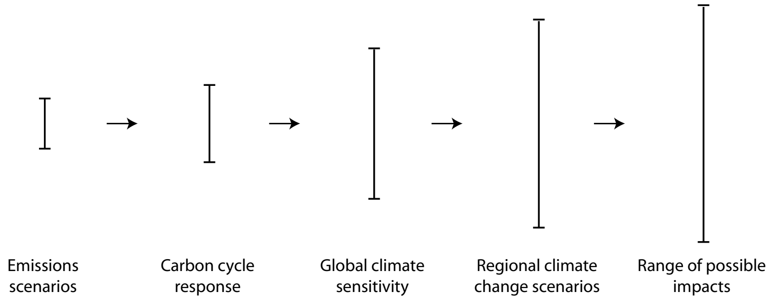
2) There is greater variability of rainfall compared to temperature making the potential greenhouse signal weaker, and

3) There is poorer spatial representation of rainfall in climate models and their poor ability to correctly simulate present-day Australian monsoon rainfall[45,69].

There is also no clear consensus as to how El Niño-Southern Oscillation (ENSO) events will change as global climate continues to warm.

There is, therefore, a range of uncertainties in projecting exactly how surface climate in northeast Australia and the GBR will change over the coming decades and century. It is clear, however, that we are committed to major global and regional climate change and that some climate variables have already shown statistically significant changes. Even if all greenhouse gas emissions were halted now, we are still committed to further significant climate change (0.1°C per decade compared with current projections of 0.2°C per decade) and sea level rise[43,70,24].

***Figure 2.3*** *'Explosion of uncertainty' in assessing the impacts of global climate change. (Source: Jones[26])*



### 2.2.5 Current projections

The most recent projections of global climate change due to the enhanced greenhouse effect suggest global average temperature could warm by 1.1 to 6.4°C over 1980 to 1999 values by 2100[24] with best estimates ranging from 1.8 to 4.0°C. These are generally consistent (although not strictly comparable) with the earlier projections of 1.4 to 5.8°C[23] and are based on more climate models of greater complexity and realism and better understanding of the climate system. These projections are for global average temperatures and contain significant geographic variations with greater warming in high latitudes compared to lower latitudes and greater warming in continental interiors compared to ocean areas. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report[24] also presents new and stronger evidence compared with the Third Assessment Report[23] that 'warming of the climate system is unequivocal', that there is 'very high confidence' that this warming is the net effect of human activities since the Industrial Revolution, and that most of the observed global warming since the mid-20th century is 'very likely' due to the observed increases in greenhouse gas concentrations. There is also mounting evidence of changes in the biosphere (even with the relatively modest climate changes observed to date) with alterations in migration patterns, distributions and seasonally-cued cycles observed in various marine, terrestrial and freshwater species all occurring in a direction that is consistent with a warming climate[6,22,44,50].

### 2.2.6 Evidence for recent warming

Compilations of instrumental global land and sea temperatures back to the mid-19th century provide strong evidence of a warming world and the recent unusual warmth, with nine of the 10 warmest years since 1850 occurring between 1997 and 2006[7,17c,24]. For Australia, 2005 was the warmest year on record with annual average temperatures 1.1°C above the 1961 to 1990 mean and average daily maximum temperatures 1.2°C above average. April 2005 witnessed the largest Australian monthly temperature anomaly ever recorded in the period back to the early 20th century, 2.6°C above the 1961 to 1990 average. The global and regional warmth of 2005 is of particular significance as there was no ENSO event. This contrasts with the exceptional warmth of 1998, by some measures the warmest year on record, when the major 1997 to 1998 ENSO event significantly contributed to above average temperatures[57] (Bureau of Meteorology[d]).

## 2.3 Current surface climate

Average seasonal surface climate in northeast Australia and the GBR is dominated by two large-scale global circulation systems, the south-easterly trade wind circulation and the Australian summer monsoon westerly circulation[60]. These effectively divide the year into the warm summer wet season (October to March) and the cooler winter dry season (April to September). This seasonality makes the 12-month 'water year', October to September, the most appropriate annual average rather than the calendar year. Tropical cyclones are an important feature of the summer monsoon circulation and can occur on the GBR between November and May with peak activity January to March[53].

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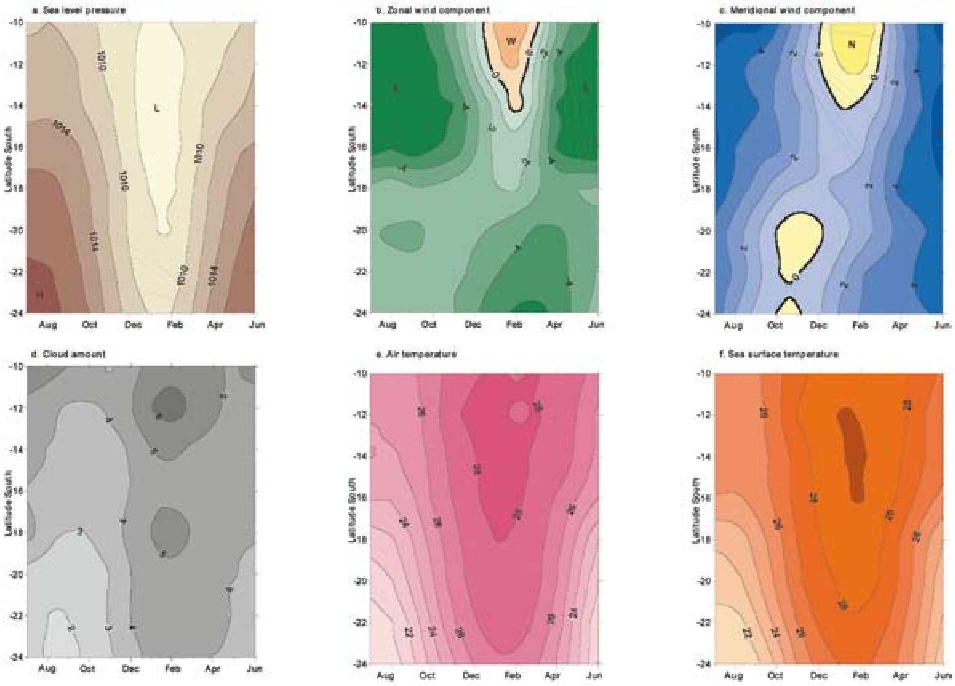
[c] http://www.cru.uea.ac.uk/cru/info/warming/

[d] http://www.bom.gov.au

### 2.3.1 Atmospheric circulation

Average monthly variations of the atmospheric circulation along the GBR (Figure 2.4) show the seasonal intrusion of the summer monsoon circulation[38,61]. This brings lower sea level pressure, greater cloud amount and weaker, moister, more westerly and northerly surface winds than found in winter. These features are most marked in January and February. Although the 'monsoon' circulation features only extend to 14 to 15° S, they introduce strong seasonality into the rainfall and river flows adjacent to the GBR. The summer monsoon displaces the belt of south-east trade winds southward in summer. In winter, much of the GBR is influenced by anticyclonic conditions, which have a more northerly location over Australia at this time of year[60]. The largest month-by-month changes in circulation typically occur from October to November although the onset of the summer monsoon does not usually occur until mid-December[18]. The monsoon retreats from about March to April. A characteristic of climate in low-latitude Australia and ENSO is the high persistence of circulation anomalies from late winter to early summer and low persistence from late summer to autumn[1,42].

***Figure 2.4*** *Monthly and latitudinal variations of average (1950 to 1997) climatic variables along the GBR for a) sea-level pressure (millibar); b) zonal wind component (metres per second, negative values indicate easterly winds); c) meridional wind component (metres per second, positive values indicate southerly winds); d) cloud amount (oktas); e) air temperature (°C); and f) sea surface temperature (°C). (Data source: NCAR/NOAA Comprehensive Ocean Atmosphere Data Set (COADS)[e], Woodruff et al.[73])*



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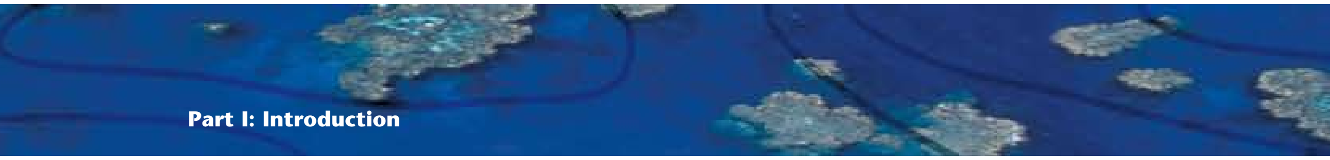
[e] http://www.dss.ucar.edu/pub/COADS_intro.html



## 2.3.2 Air and sea surface temperatures

Monthly mean air and sea surface temperatures (SST) show a similar distribution with annual maxima from January to February and minima in August. Greatest seasonal warming of SSTs occurs from October to September (1.4 to 1.7°C) and greatest seasonal cooling from May to June (1.1 to 1.8°C). SSTs tend to be warmer than air temperatures throughout the year, the difference being greater in winter than in summer. Monthly mean SSTs range from greater than 29°C in summer in the north to less than 22°C in winter in the south. The annual range of SSTs is approximately 4°C in the north and approximately 6°C in the south. The variability of monthly SSTs (standard deviation) is typically 0.4 to 0.6°C and is similar for different months and latitudes. The range between maximum and minimum SSTs is 2 to 3°C. These statistics are based on large-scale averages and the range of SST variability observed on coral reefs can be much greater. For example, at the offshore Myrmidon Reef automatic weather station[f], the average diurnal SST range is 1°C and average daily SSTs vary between a minimum of 24°C in the last week of August to a maximum of 29°C in the first week of February (4.8°C range). The difference between the observed daily maximum and minimum SSTs is 9.5°C. Thus, the range of SSTs experienced by tropical marine organisms is much larger than the 2 to 3°C obtained from the large-scale monthly statistics. These large-scale averages also disguise the tendency for SSTs in inshore, shallower waters to be warmer in summer and cooler in winter compared to offshore deeper waters. Despite differences in absolute average SSTs along the GBR, SST anomalies (ie unusually cool or warm waters) tend to vary coherently throughout the region indicating strong, large-scale controls[30,34].

## 2.3.3 Rainfall

The summer monsoon circulation brings the majority of the annual rainfall to northeast Australia with approximately 80 percent of the annual total occurring in the summer half year[32,33]. Rainfall is, however, highly variable within the summer monsoon season and usually occurs in several bursts of activity often linked to the progression of the 30 to 60 day Madden Julian Oscillation[19,18,61]. Rainfall typically occurs on only 30 percent of days in summer and only 14 percent of days in winter. There is also considerable inter-annual variability in rainfall. At Townsville, for example, median October to September rainfall over the period 1941 to 2005 was 1036 mm, with 86 percent of the total occurring in the summer half of the year. The wettest year was 1974 with 2158 mm (more than twice the long-term median) and the driest year was 1969 with 398 mm. All months from April to December have experienced no rainfall in some years and even for the wettest months, January to March, minimum monthly rainfall was less than 10 mm. Due to the high spatial and temporal variability of rainfall, the long-term average is not a good guide to the amount of rainfall that can be expected. The median is a more appropriate statistic as it is not influenced by the extreme high and low values that are common in eastern Australia (as it is for river flow). All coastal rainfall sites show maximum rainfall and greatest variability during the summer monsoon from December to March and, despite differences in total rainfall received, the annual distribution of rainfall is similar along the coast[35]. As with SSTs, rainfall anomalies in northeast Queensland tend to vary coherently[29,31,33].

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[f] http://www.aims.gov.au/pages/facilities/weather-stations/weather-index.html

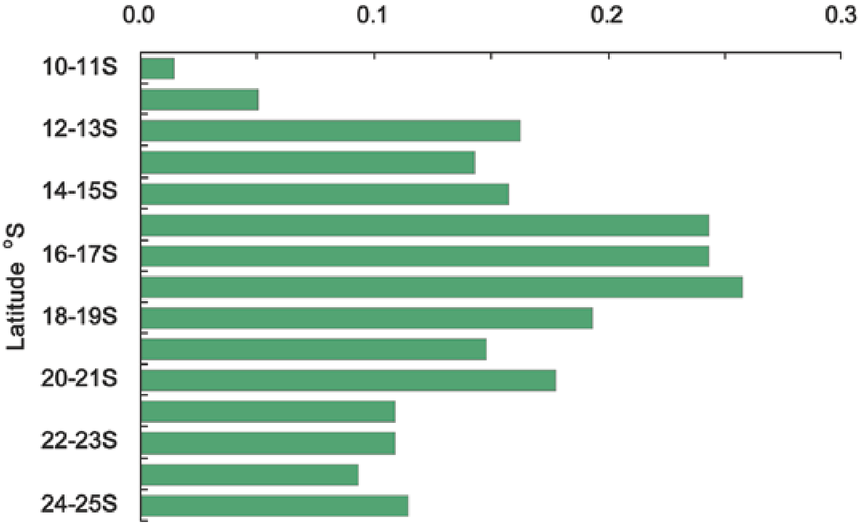
### 2.3.4 River flow

The highly seasonal and highly variable rainfall regime of northeast Australia also results in highly variable river flows. This extreme variability is characteristic of Australian rivers in comparison to other regions of the world[15,9]. The majority (about 80 percent) of total river flow into GBR coastal waters occurs between 17° S and 23° S with greatest annual flow in March, a month after the rainfall maxima. Over the period 1924 to 2005, median total flow of all rivers entering the GBR was 20 km$^3$ with a maximum of 94 km$^3$ in 1974 and minimum of 4 km$^3$ in 1987[16].

### 2.3.5 Tropical cyclones

Tropical cyclones during the summer monsoon season are the most spectacular and destructive weather systems affecting the GBR. Conditions suitable for tropical cyclone development occur from November through May. During the period 1969 to 1997, tropical cyclones were observed on the GBR from December through May with highest numbers in January and February[53]. The total number of tropical cyclone days (defined as a day with a tropical cyclone within a given area) along the GBR is highest at 16° S to 18° S and lowest at 10° S to 12° S (Figure 2.5). Tropical cyclones bring destructive winds and waves and heavy rainfall as they cross the GBR and when making landfall can cause elevated sea levels and destructive storm waves (storm surge) as well as high rainfall totals and rapid increases in river flows.

***Figure 2.5*** *Average number of tropical cyclone days per year for 1° latitudinal bands along the Great Barrier Reef, 1968–1969 to 2002–2003 showing highest activity 15 to 18° S. (Data source: Australian Bureau of Meteorology)*



### 2.3.6 Inter-annual variability: El Niño-Southern Oscillation

Average surface climate conditions in northeast Australia and the GBR include high inter-annual variability especially for rainfall and river flow. At any given time climatic conditions are likely to differ from these average conditions and are thus termed anomalies. The major source of global short-term climate variability and predictability is the ENSO phenomenon[40]. ENSO events are also the major source of inter-annual climate variability in northeast Australia and along the GBR[32]. ENSO describes the aperiodic variations in the ocean-atmosphere climate of the tropical Pacific, which due to linkages operating through the large-scale atmospheric circulation called teleconnections, causes climate anomalies in many parts of the tropics and extra-tropics[2,40]. ENSO has two phases:

1) El Niño events when the eastern equatorial Pacific is unusually warm, and

2) La Niña events when the eastern equatorial Pacific is unusually cold.

Events typically evolve over 12 to 18 months and, once initiated, their development is to some extent predictable though individual events can develop and decay differently[41]. Distinct climate anomalies occur in northeast Australia and along the GBR with ENSO extremes[32]. During typical El Niño events, the summer monsoon circulation is weaker than normal associated with higher sea level pressure and more south-easterly winds. Cloud amount is reduced with consequent higher radiation and rainfall and river flows are considerably lower than normal (eg for Townsville median rainfall in El Niño years is 779 mm compared to long-term median of 1036 mm). During typical La Niña events, the summer monsoon circulation is stronger than normal with lower sea level pressure and more north-westerly winds. Cloud amount, rainfall and river flows are higher than average (eg for Townsville median rainfall in La Niña years is 1596 mm). Burdekin River flow in El Niño years is 3.8 km$^3$ compared with 9.2 km$^3$ in La Niña years. SST anomalies along the GBR are more marked during El Niño than La Niña events[35] (Figure 2.6), with, in particular, warmer than average SSTs occurring during the summer warm season. The differences in the strength of the summer monsoon circulation with ENSO also results in marked differences in the occurrence of tropical cyclones along the GBR with much less activity during El Niño years (Figure 2.7). Overall, the level of disturbance to the GBR appears to be greater during La Niña events when the more vigorous summer monsoon circulation and heightened tropical cyclone activity causes enhanced rainfall and river flow. This is likely to lead to reduced salinity and higher turbidity of GBR waters and increased levels of physical disturbance. Suppression of the summer monsoon and tropical cyclone activity during El Niño events is associated with reduced rainfall and river flow inputs to the GBR and maintenance of more winter-like conditions.

**Figure 2.6** *Average monthly sea surface temperature anomalies (°C, from ENSO-neutral) years for 1° latitude bands along the GBR over the 24-month period of 21 El Niño events (left) and 21 La Niña events (right). Filled bars indicate anomalies significantly different from those averaged for ENSO-neutral years at the 5 percent level. Thin black line is average monthly annual cycle. Illustrates the 'typical' GBR SST signals associated with ENSO extremes and their relation to the annual cycle. (Data source: HadISST, 1871 to 2005, Rayner et al.[54])*

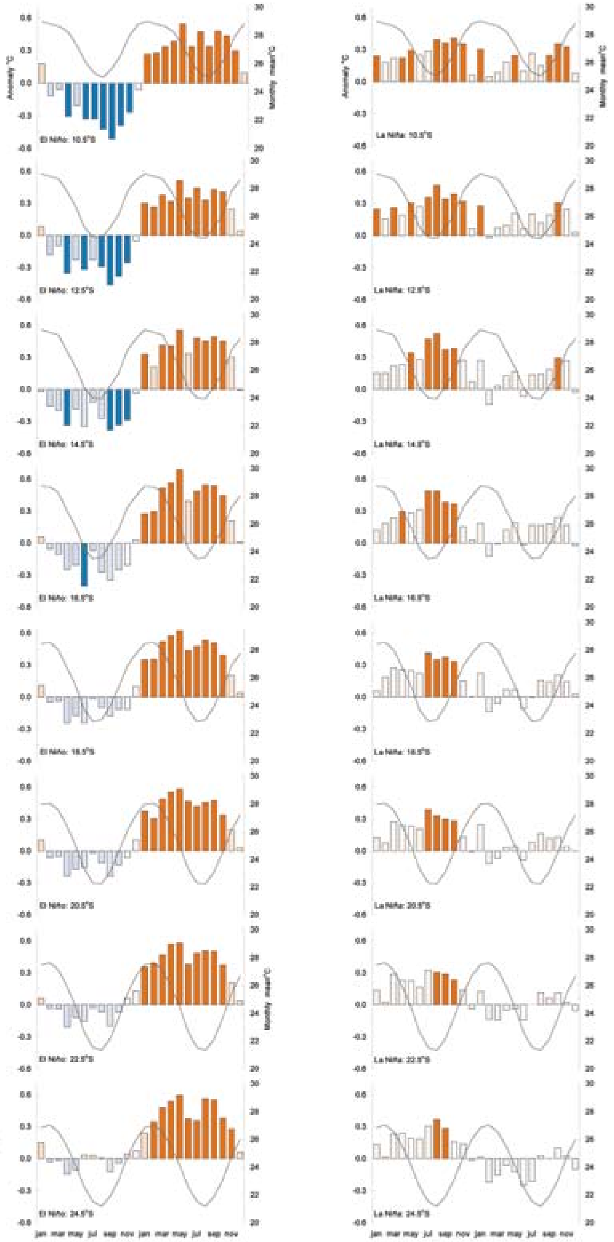
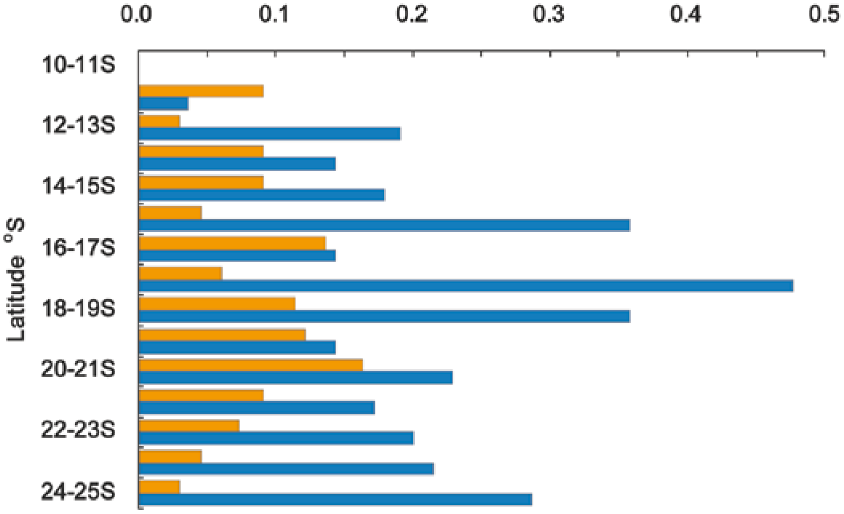


***Figure 2.7*** *Average number of tropical cyclone days per year for 1° latitudinal bands along the GBR for El Niño (orange, 11 events) and La Niña years (blue, 7 events) during period 1968–1969 to 2002–2003, illustrating the suppressed activity during El Niño events. (Data source: Australian Bureau of Meteorology)*



## 2.3.7 Decadal variability: Pacific Decadal Oscillation

The strength of the relationship between ENSO extremes and regional climate, including northeast Australia and the GBR, is modulated on decadal timescales by the Pacific Decadal Oscillation (PDO also known as the Inter-decadal Oscillation). This is an El Niño-like pattern of climate variability in the Pacific Ocean[37] that is characterised by persistent warm (1925 to 1946; 1977 to 1998) and cold (1890 to 1924; 1947 to 1976) regimes. Relationships between Australian rainfall and ENSO events are strong, significant and more predictable during PDO cool phases and weak, insignificant and less predictable during PDO warm phases[52].

For northeast Australia, PDO cool regimes are associated with significant correlations between rainfall and indices of ENSO strength (eg Niño 3.4 SST index[g]), greater spatial coherence of rainfall anomalies and greater inter-annual variability of rainfall (ie larger extremes). During PDO warm phases, the opposite conditions prevail with insignificant correlations with ENSO, less spatially coherent rainfall anomalies with reduced inter-annual rainfall variability (Table 2.1). These decadal variations also affect river flow entering the GBR.

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[g] http://www.cpc.noaa.gov/data/indices/

***Table 2.1*** *Decadal modulation of Queensland October to September rainfall characteristics and ENSO teleconnections by PDO phase*

| | PDO phase | Standard Deviation rainfall percent | Correlation rainfall and Niño 3.4 index of ENSO | Percent explained variance by PC1* | Maximum rainfall percent | Minimum rainfall percent |
|---|---|---|---|---|---|---|
| 1891 to 1924 | Cool | 28 | -0.60 | 53 | 167 | 31 |
| 1925 to 1946 | Warm | 15 | -0.15 | 35 | 120 | 59 |
| 1947 to 1976 | Cool | 33 | -0.79 | 62 | 196 | 49 |
| 1977 to 1998 | Warm | 16 | -0.11 | 31 | 130 | 77 |
| 1891 to 2005 | | 26 | -0.54 | 48 | 196 | 31 |

* PC1 = First Principal Component

## 2.4 Observed and projected climate

In this Section, observed changes in climate in the vicinity of the GBR are first described for the various climate variables (the Bureau of Meteorology has instrumental records of climate change for Australia[h]). Projections as to how these are likely to change and the level of confidence in such changes with continued climate change are then discussed. These are summarised in Table 2.2 for the years 2020 and 2050 and are based on two IPCC Special Report on Emissions Scenarios (SRES; Appendix 2.1): SRES A2 (most extreme scenario with $CO_2$ by 2100 three times pre-industrial concentration) and SRES B1 (least extreme scenario with $CO_2$ by 2100 two times pre-industrial concentration). Various published climate projections for the region are based on a variety of dates into the future[69] (eg 2070). As a general rule of thumb, air temperature changes in tropical and coastal Australia are approximately the same as the average global warming for any given scenario and time into the future[51]. Similarly, L.D.D. Harvey (pers comm 2006) has estimated that summer SST warming in the vicinity of tropical reefs is likely to be 80 to 90 percent of average global change for a given scenario and time into the future. This is higher than suggested by IPCC[23] for annual average tropical SSTs, which tend to be half the global average temperature change.

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[h] http://www.bom.gov.au/silo/products/cli_chg/

***Table 2.2*** *Projected changes in climate for the Great Barrier Reef region for 2020 and 2050 based on SRES A2 and B1 storylines (see Appendix 2.1)*

| | 2020 | | 2050 | |
|---|---|---|---|---|
| **Projected change** | **A2** | **B1** | **A2** | **B1** |
| Air temperature (relative to 1961 to 1990 average and on basis that tropical and coastal areas of Australia will warm at ~global average[51]) | +1.4°C | +0.6°C | +2.6°C | +0.9°C |
| Air temperature extremes | See Table 2.3 with example for Townsville temperature extremes and warming of 1°C | | | |
| SST for GBR (relative to 1961 to 1990 average 25.9°C) | +0.5°C | +0.5°C | +1.2°C | +1.1°C |
| Rainfall | No consensus on change in average precipitation however<br>1) intensity of drought associated with given rainfall deficit will be increased due to higher air temperatures<br>2) intensity of high rainfall events will increase (eg January 1998 Townsville flood event more frequent)<br>3) more extremes | | | |
| Tropical cyclones | No consensus on changes in frequency or spatial occurrence but intensity of tropical cyclones expected to increase, so that although there may not be more tropical cyclones or in new locations but severe tropical cyclones (eg TC Ingrid, TC Larry) likely to be more common (possibility already being muted of a higher category than 5) | | | |
| Sea level rise (relative to 1961 to 1990 baseline) | +38cm | +7cm | +68cm | +13cm |
| Ocean chemistry (estimated decrease in ocean pH based on projections of 0.3 to 0.5 decrease by 2100) | -0.10 | -0.06 | -0.25 | -0.15 |
| ENSO | No consensus on how ENSO frequency and intensity will change but likely to be continued source of aperiodic disturbance in region | | | |
| $CO_2$ parts per million (pre-industrial = 270 ppm) | 440 | 421 | 559 | 479 |

### 2.4.1 Air temperatures

#### *Observed*

Instrumental records since the end of the 19th century show that global temperatures have significantly warmed by about 0.7°C[7,17,24]. Average, maximum and minimum air temperatures over Queensland have significantly warmed since the start of reliable records in the early 20th century (Figure 2.8). The largest changes to date have been observed in minimum temperatures and in winter of approximately 0.9°C (Figure 2.9). These observed changes in average temperatures have been accompanied by changes in daily temperature extremes with more extreme hot days and nights and fewer cold days and nights (Figure 2.10).

***Figure 2.8*** *Instrumental annual anomalies from 1961 to 1990 mean for a) Queensland maximum air temperatures and b) Queensland minimum air temperatures, 1910 to 2006. Thick line is 10-year Gaussian filter emphasising decadal variability. (Data source: Australian Bureau of Meteorology, Lough[33])*

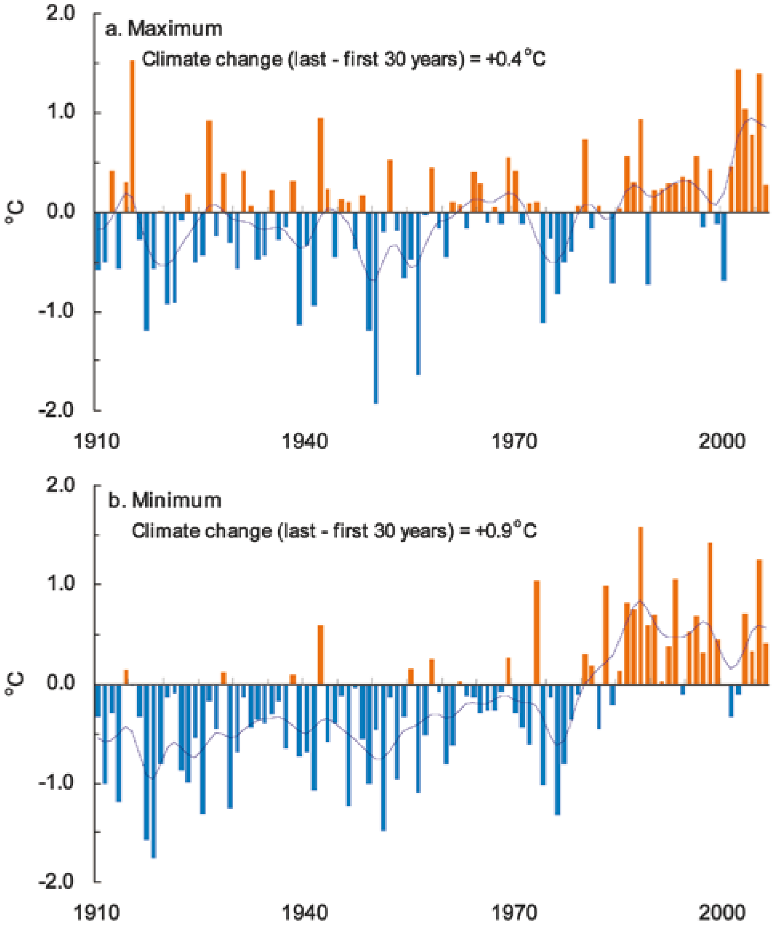


***Figure 2.9*** *Differences in monthly average (black), maximum (red) and minimum (blue) air temperatures for Queensland, 1977–2006 minus 1910–1939. Filled bars show months where observed changes are significant at the 5 percent level. Illustrates warming has been observed in all months with significant changes most evident for minimum and average air temperatures. (Data source: Australian Bureau of Meteorology, Lough[33])*

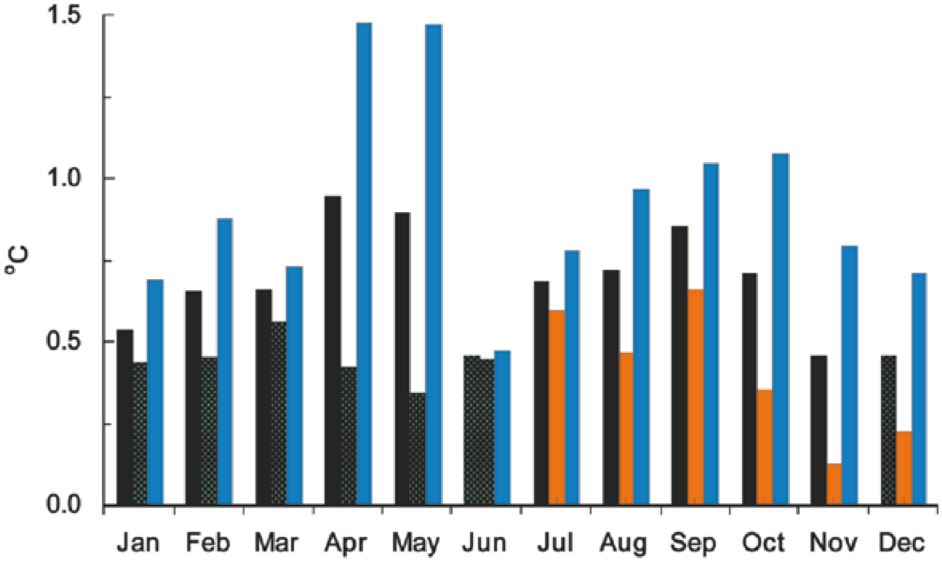
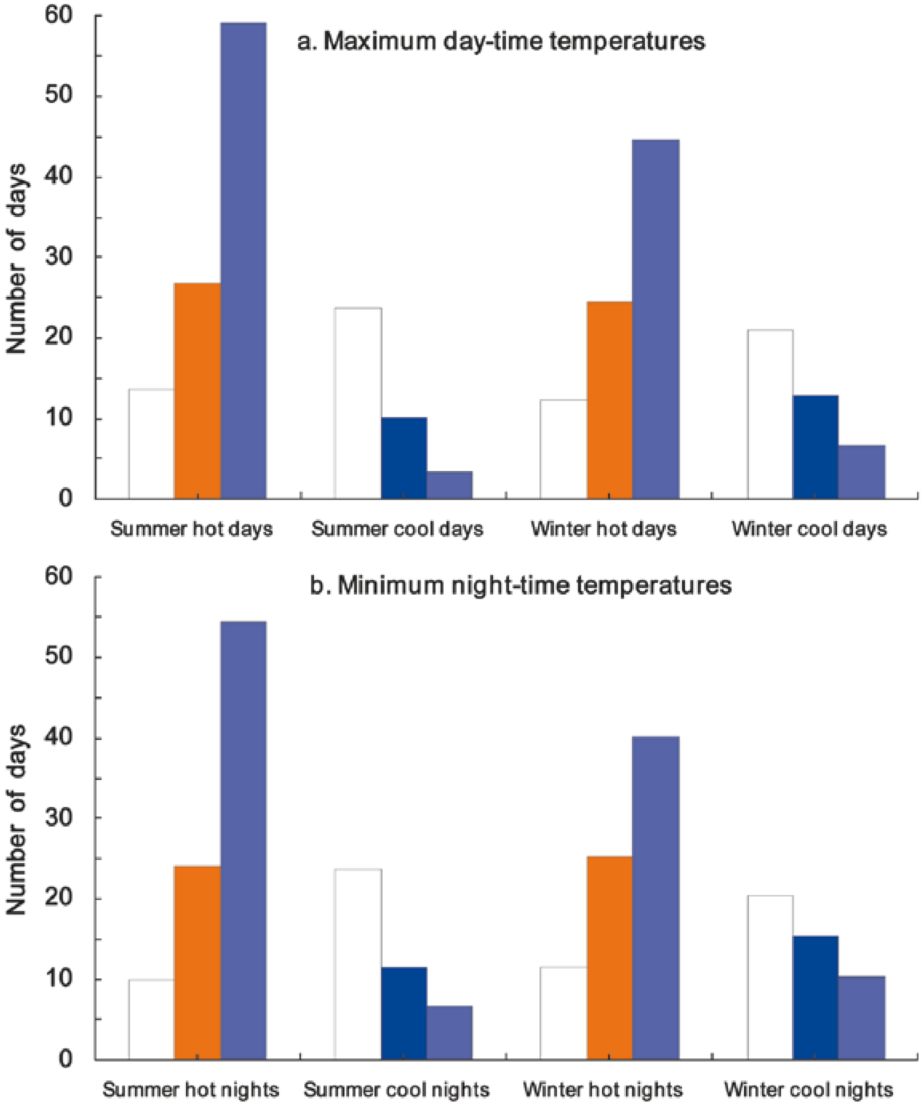


***Figure 2.10*** *Observed changes in average number of extreme summer and winter a) day-time and b) night-time temperatures for Townsville, Queensland. Based on counts of number of days above 90th percentile (red bars) and below 10th percentile (blue bars) for 1941 to 1960, 1986 to 2005 and projected number with 1°C warming (grey bars). Illustrates already observed increase in extreme hot days and nights and reduction in cool days and nights. (Data source: Australian Bureau of Meteorology)*



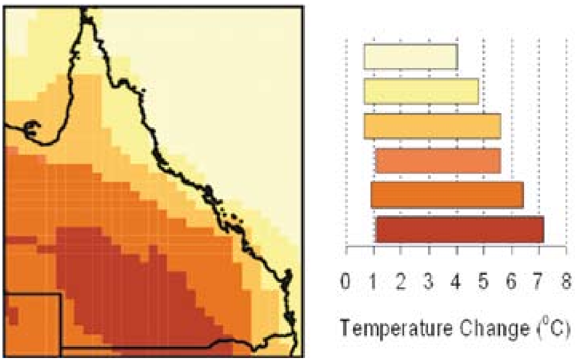
### *Projected*

There is good agreement between different climate models as to the direction and magnitude of continued warming in northeast Australia. Regional models suggest slightly lower warming along the Queensland coastal strip compared to interior Queensland[65,69,21] (Figure 2.11a and b). Coastal air temperatures are projected to increase (above 1990 levels) by as much as 4 to 5°C by 2070[69] (Table 2.2 for 2020 and 2050). This projected warming will increase the frequency of occurrence of warm temperature extremes and decrease the number of cold temperature extremes (Table 2.3 gives examples of changes in maximum daytime and minimum night time temperature extremes for Townsville with 1°C global warming[21]).

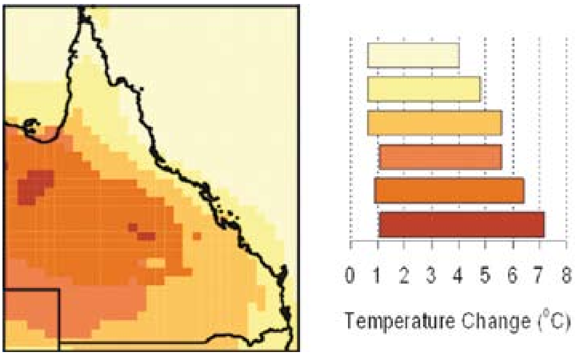
**Certainty:**
High, statistically significant warming already observed and projected to continue

**Regional projection:**
Greater warming inland than along coastal strip

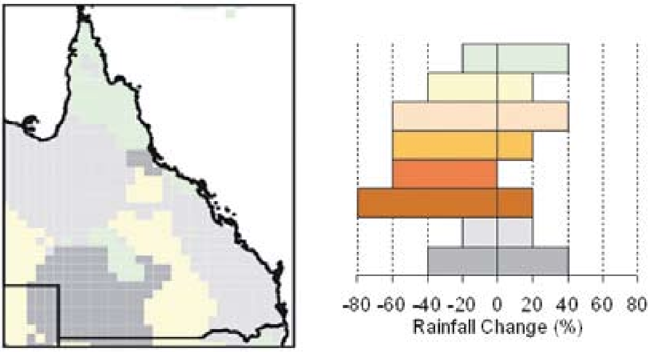
***Figure 2.11*** *Regionally based seasonal temperature and rainfall projections for Queensland to 2070. Horizontal bars indicate the ranges from several different climate models (Source: Whetton et al.[69])*



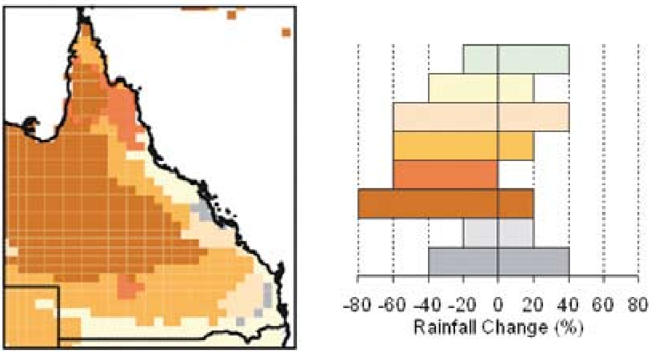
*a. Summer temperature*



*b. Winter temperature*



*c. Summer rainfall*



*c. Winter rainfall*

***Table 2.3*** *Example of changes in air temperature extremes for Townsville associated with a 1°C warming (ie by 2020 for A2 and by 2050 for B1 scenarios)*[i]

| **Warm extremes** | Summer number of days above 33°C | Winter number of days above 30°C | Summer number of nights above 26°C | Winter number of nights above 21°C |
|---|---|---|---|---|
| 1961 to 1990 | 16 | 15 | 18 | 20 |
| +1°C warming | 59 | 45 | 55 | 40 |
| **Cold extremes** | Summer number of days below 28°C | Winter number of days below 24°C | Summer number of nights below 20°C | Winter number of nights below 11°C |
| 1961 to 1990 | 16 | 19 | 20 | 17 |
| +1°C warming | 3 | 7 | 7 | 10 |

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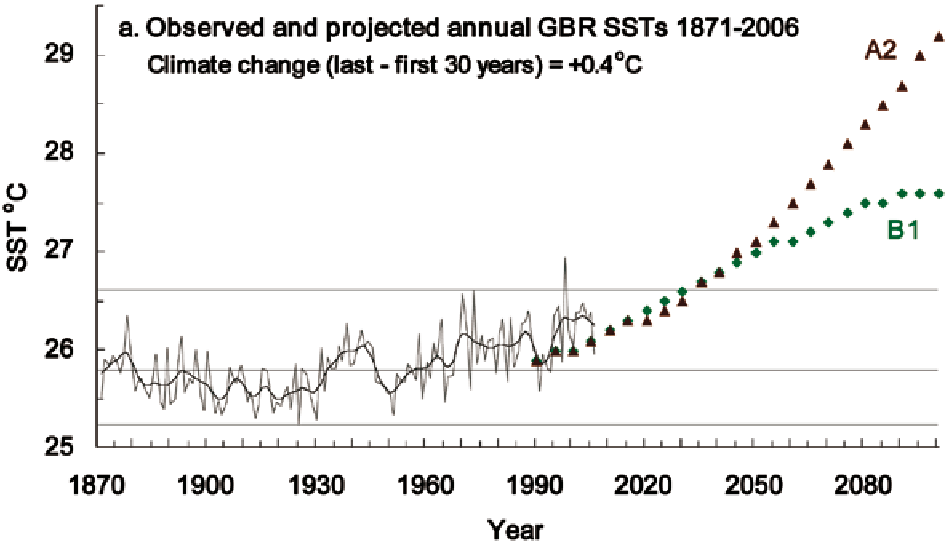
[i] Based on 90th and 10th percentiles of daily maximum and minimum temperatures at Townsville Bureau of Meteorology station

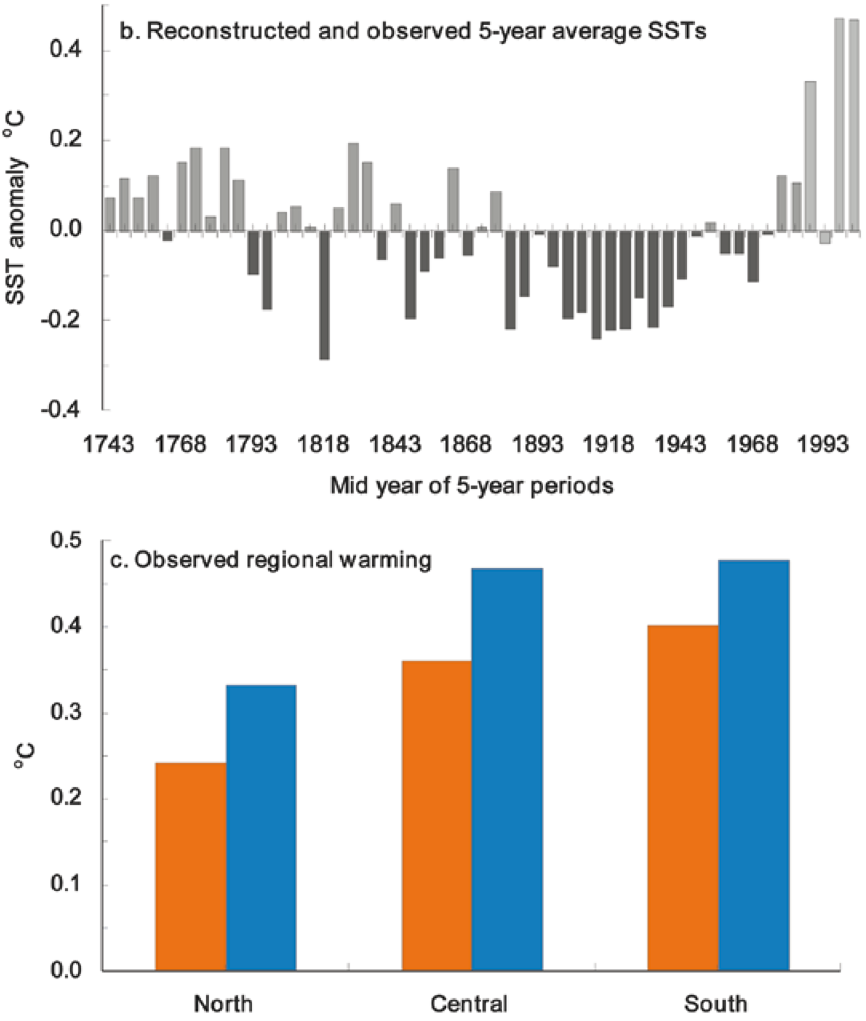
### 2.4.2 Sea surface temperatures

*Observed*

Globally, SSTs have warmed significantly as global climate has warmed over the past century[23]. There is also recent evidence that this warming is not just occurring at the surface and that the heat content of the global oceans has increased since 1960[4]. Average SSTs of the GBR have significantly warmed since the end of the 19th century with average temperatures for the most recent 30 years (1976 to 2005) 0.4°C warmer than the earliest instrumental 30 years (1871 to 1900; Figure 2.12a). Combining reconstructions from coral records and the recent instrumental record suggests that SSTs in the GBR are now warmer than they have been since at least back to the mid-17th century[36]. Figure 2.12b shows reconstructed SST from Sr/Ca ratios measured in up to seven coral cores from the central GBR by Hendy et al.[20] who note 'SSTs for the 18th and 19th centuries that are as warm as, or warmer than the 20th century'. The observed warming of the GBR has also been greater in winter than in summer and greater in the central and southern GBR than in the northern GBR (Figure 2.12c).

***Figure 2.12*** *a) Observed (1871 to 2006) and projected (to 2100 for SRES A2 and B1 scenarios) annual sea surface temperatures for the GBR. Thick black line is 10-year Gaussian filter emphasising decadal variability; central black line is observed average annual SST, 1871 to 1989 (25.8 oC) and grey lines indicate observed maximum and minimum values. (Data sources: HadISST, NOAA OI.v2 SST and ReefClim, Roger Jones, CSIRO). b) Reconstructed (1741 to 1985) and observed (1985 to 2005) average 5-year sea surface temperature anomalies (from long-term average) for the GBR. This coral series ends in 1985. c) Observed warming (1977 to 2006) minus (1871 to 1900) summer (red) and winter (blue) sea surface temperatures in the north, central and southern GBR. All differences significant at the 5 percent level. Greatest warming observed in winter and in central and southern GBR*





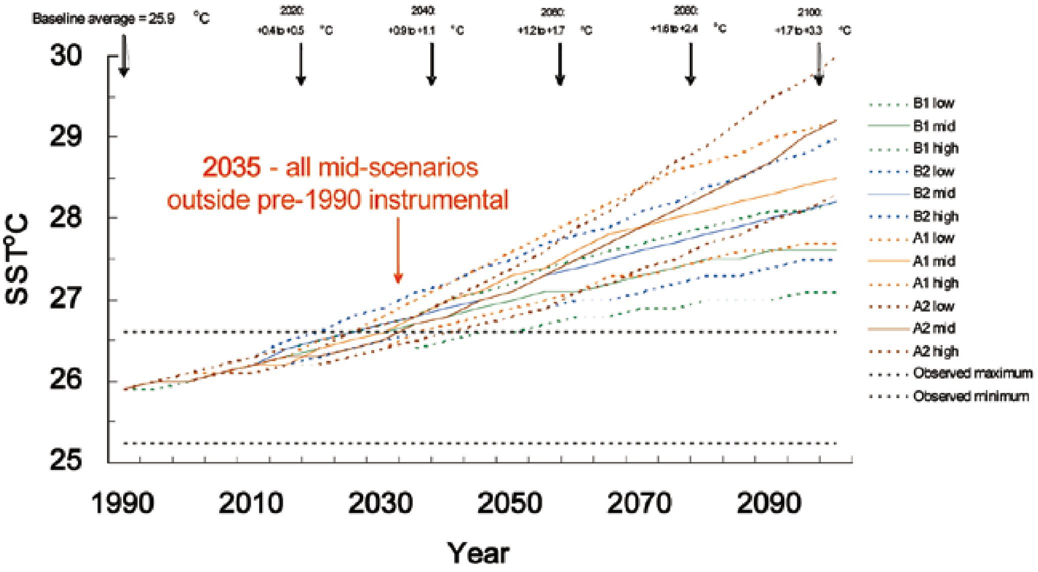
### *Projected*

Average annual SSTs on the GBR are projected to continue to warm over the coming century and could be between 1 and 3°C warmer than present temperatures by 2100 (Figure 2.13). Whatever climate scenario is used, all projections are outside the observed GBR SST climate range up to 1990 by the year 2035. However, these scenarios do not show any differences in projected warming with either latitude or season. This does not mean that there will not be such spatial and seasonal changes and, based on observed trends, it is likely that SSTs might warm more in winter and in the southern GBR. Projected average SSTs by 2020 could be 0.5°C warmer and greater than 1°C warmer by 2050 (Table 2.2). There is no indication in current climate projections as to how SST extremes will change but it is likely that they will follow a similar path as air temperatures extremes (see Townsville example in Table 2.3) with a shift towards more warm SST extremes and reduction in cold SST extremes.

**Certainty:**
High, statistically significant warming already observed and projected to continue

**Regional projection:**
Greater warming in southern GBR and in winter

***Figure 2.13*** *Range of GBR annual sea surface temperature projections through 2100 for various SRES scenarios and climate sensitivities. (Data source: ReefClim, Roger Jones, CSIRO)*

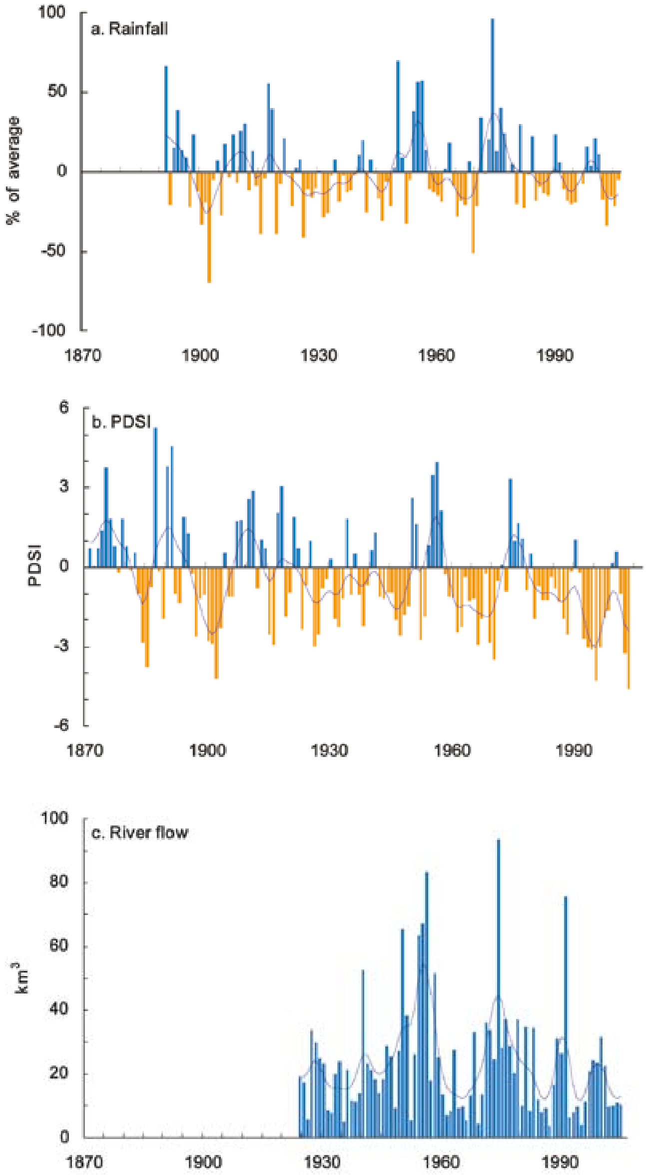


## 2.4.3 Rainfall and river flow

### *Observed*

Observed variations of Queensland rainfall (Figure 2.14a) over the past century show high inter-annual and decadal variability with 1902 (culmination of the federation drought), the driest year on record, and 1974 the wettest. The 1950s and 1970s were characterised by above average rainfall. Calculation of a linear trend from the 1950s indicates decreasing rainfall over northeast Australia but this is due to the wetter conditions of this decade and there is no overall trend towards wetter or drier conditions. Warmer air temperatures have, however, increased the intensity of observed drought conditions for a given rainfall deficit[48,11] (Figure 2.14b). High inter-annual and decadal variability (similar to rainfall) also characterises freshwater inputs to the GBR[16] (Figure 2.14c) but, again, there is no long-term trend in the amount of freshwater entering the GBR lagoon. The spatial extent of freshwater associated with seasonal flood plumes modelled by King et al.[27] illustrates the range of extremes in minimum salinity affecting tropical marine ecosystems (Figure 2.15).

***Figure 2.14*** *a) Queensland October-September rainfall index, 1891 to 2006, as percent anomaly from long-term mean; b) East tropical Queensland October-September Palmer Drought Severity Index (which uses both rainfall and temperature), 1871 to 2003; and c) All-river October-September flow into GBR lagoon. Thick line is 10-year Gaussian filter emphasising decadal variability. Only the PDSI shows a significant downward trend towards more intense droughts. (Data sources: Australian Bureau of Meteorology, Lough[29j], Dai et al.[11], Furnas[16])*



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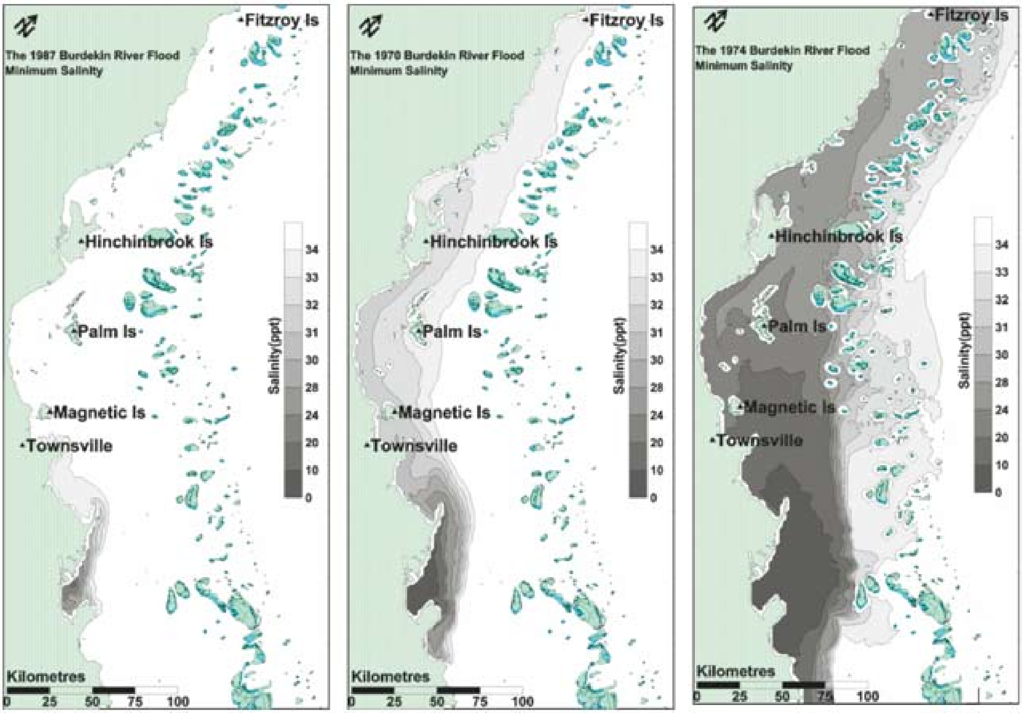
[j] http://www.cdc.noaa.gov/cdc/data.pdsi.html

***Figure 2.15*** *Modelled minimum salinity for the GBR for a) 1987 representing a dry year; b) 1970 representing an average year; and c) 1974 representing the wettest year on record. (Data source: King et al.[27])*



### *Projected*

General global projections for a warmer world are for an enhanced hydrological cycle with more extreme droughts and floods and enhanced evaporation[23,24]. Regional projections for changes in average rainfall in northeast Queensland are, however, less clear. This is due, in part, to the poor ability of current climate models to correctly simulate the Australian summer monsoon[45], and the resulting uncertainty amongst different climate models about the direction and magnitude of change[69,21] (Figure 2.11c and d). Interpretation of regional changes is also confounded by the high natural inter-annual variability of regional rainfall and river flow and, again, the uncertainty introduced into projections by lack of knowledge as to how ENSO events might change in a warmer world. As already observed, however, it is likely that a given rainfall deficit in a warmer world will result in greater drought conditions than the same rainfall deficit in the early 20th century. This is due to higher temperatures increasing evaporative losses, decreasing soil moisture and, thus, the intensity of drought conditions and reduced river flows[65]. Most climate models project increases in extreme daily rainfall events – even where projected changes in average rainfall are small or unclear[65]. The intensity of extreme rainfall events such as the January 1998 Townsville flood event might become more common.

In the absence of clear projections as to changes in average rainfall and river flow, it can be assumed that inter-annual and decadal variability of northeast Australian rainfall and river flow (and modulation by ENSO and PDO) will continue in a warmer world[64]. The magnitude of droughts and high intensity rainfall events are likely to be greater in a warmer world compared to current climate conditions, with consequent effects on river flow and the spatial extent of flood plumes affecting the GBR. Thus, the observed extremes of very low flow years and very high flow years (Figure 2.15 left and right) are likely to be more common.

**Certainty:**
Low for regional changes in average rainfall and river flow but extremes likely to be greater

**Regional projection:**
Similar spatial and inter-annual variability modulated by ENSO and PDO

## 2.4.4 Tropical cyclones

### *Observed*

There is mounting observational evidence that the destructive potential of tropical cyclones around the world has increased in recent decades[14,68]. For the Australian region, there is evidence from the period 1970 to 1997 that despite a decrease in the number of tropical cyclones, there was an increase in the number of intense cyclones[49]. Puotinen et al.[53] provide the most detailed description of the occurrence and intensity of tropical cyclones affecting the GBR over the period 1969 to 1997. Over this period, there were no category 5 and only two category 4 tropical cyclones (The Australian Bureau of Meteorology uses a 5-point scale for categorising the intensity of tropical cyclones. The most severe, category 5, has maximum wind gusts greater than 279 km per hour, average wind speeds greater than 200 km per hour and central pressures less than 930 hectoPascal. This category is equivalent to categories 4 to 5 on the Saffir-Simpson scale used in the United States[k]). Although there has been an apparent decline in the number of tropical cyclone days affecting the GBR (Figure 2.16), Tropical Cyclone Ingrid (category 4) and Tropical Cyclone Larry (category 5) occurred in 2005 and 2006, respectively. This possible increase in severe tropical cyclones is consistent with the suggestion of Nicolls et al.[49] that although the number of tropical cyclones may have declined, the intensity of those that occur is greater.

### *Projected*

Although warmer water temperatures might be expected to increase the intensity of tropical cyclones, their formation depends upon a number of other factors[60]. It is, however, likely that tropical cyclones in a warming world will be more intense with higher maximum wind speeds and greater rainfall[24]. Although there are no clear indications that the number and preferred locations of tropical cyclones will change in the Australian region, there is some evidence that their intensity will increase as measured, for example, by higher maximum wind speeds[65,66]. More intense tropical cyclones will also interact with higher sea levels to produce more devastating storm surges and coastal inundation

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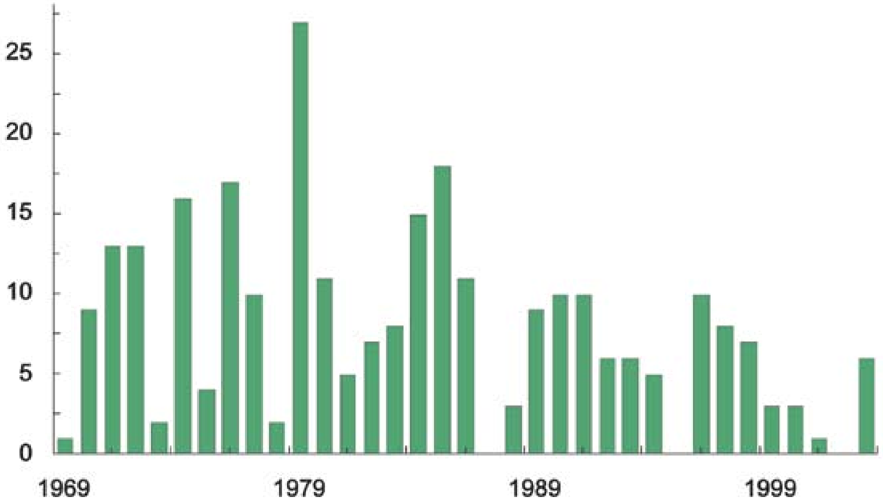
[k] http://www.bom.gov.au/weather/wa/cyclone/about/faq/faq_def_2.shtml

***Figure 2.16*** *Annual number of tropical cyclone days within the GBR, 1969 to 2003 (Data source: Australian Bureau of Meteorology)*



in a warmer world[39]. As an example of what this might mean, category 3 Tropical Cyclone Althea, which affected Townsville in December 1971, was associated with a storm surge of 3.7 metres above normal tide but occurred during a low tide, thus minimising the effects. With rising sea level, a 3.7 metre storm surge could become a 3.8 to 8.7 metre storm surge by 2100 that, if added to a typical high tide in Townsville (4.1 metres on 9 February 2005), would result in a local sea level surge of 7.9 to 12.8 metres.

It can be assumed, therefore, that tropical cyclones will continue to exert an aperiodic influence on the GBR with a similar spatial and seasonal distribution in occurrence as present. Inter-annual variations in tropical cyclone activity are also likely to continue to be modulated by ENSO events with more activity during La Niña and less during El Niño years. Changes in ENSO extremes in a warmer world will also affect tropical cyclone occurrence, frequency, and associated impacts on the GBR. The intensity of tropical cyclones may however, increase with severe tropical cyclones such as Tropical Cyclone Ingrid (March 2005) and Tropical Cyclone Larry (March 2006) being more characteristic of the future climate than the recent past.

**Certainty:**
Moderate to high that the intensity of tropical cyclones will increase but low as to whether there will be changes in location and frequency

**Regional projection:**
Similar spatial distribution – modulated by ENSO

## 2.4.5 Sea level

### *Observed*

As global climate warms, sea level rises due to thermal expansion of the oceans and the contribution of additional water through the melting of mountain glaciers and continental ice sheets. As a result, sea level appears to be rising at a rate of 1 to 2 mm per year. A recent reconstruction of global mean sea level from 1870[10] indicates that between January 1870 and December 2004, global sea level rose by 195 mm. The authors also found observational evidence (matching climate model simulations) of a significant acceleration in the rate of global sea level rise of 0.13 ± 0.006 mm per year. The observed trend in sea level for Cape Ferguson, near Townsville, from September 1991 through May 2006 is 2.9 mm per year[47].

### *Projected*

If the observed acceleration in sea level rise[10] continues to 2100, then global sea level would be 310 ± 30 mm higher than in 1990. This corresponds to the middle of the IPCC[23] projected range of sea level rise of 100 to 900 mm and a narrower range of 180 to 590 mm of the IPCC[24] by 2100. These ranges may however, be higher as the Greenland ice sheet appears to be melting faster than expected[12,63]. There will also be regional variations in the magnitude of sea level rise due to local tectonic changes (though these are minimal in Australia), ocean circulation patterns and inter-annual variability modulated, for example, by ENSO events. How much land inundation occurs for a given sea level rise depends on coastal characteristics. For example, a 1 metre sea level rise will be associated with a 100 metre recession for a sandy beach. Continued sea level rise is a certainty and even if greenhouse gas emissions were halted at 2000 levels, sea level would continue to rise at about 10 cm per century due to thermal inertia of the climate system[43,70], and 'substantial long-term change may be impossible to avoid'.

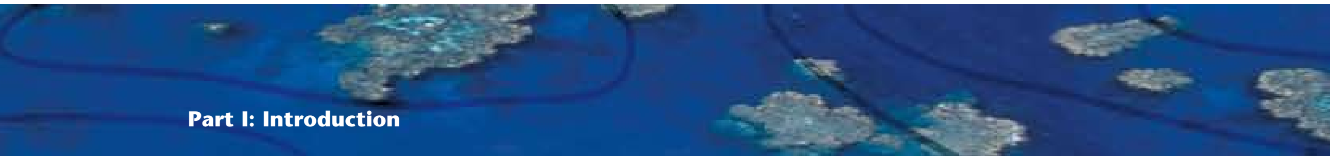
**Certainty:**
High that sea level has and will continue to rise and the rate may accelerate

**Regional projection:**
Limited, regional up to 0.68 metre increase by 2050, global 0.1 to 0.9 metre increase by 2100

## 2.4.6 Ocean chemistry

### *Observed*

The oceans absorb carbon dioxide ($CO_2$) from the atmosphere and are estimated to have absorbed about half of the excess $CO_2$ released into the atmosphere by human activities in the past 200 years. About half of this anthropogenic $CO_2$ is in the upper 10 percent of oceans (less than 1000 metres depth) due to slow ocean mixing processes. This absorbed $CO_2$ is resulting in chemical changes in the ocean, which it is estimated has already caused a decrease in oceanic pH of 0.1[55,28]. This is referred to as ocean acidification as the oceans are becoming more acidic, though they are still alkaline.



### *Projected*

With continued emissions of $CO_2$, oceanic pH is projected to decrease by about 0.4 to 0.5 units by 2100 (a change from 8.2 to 7.8 associated with a surface water decrease in $CO_{3-}$ by 47 percent of pre-industrial levels). This is outside the range of natural variability and a level of ocean acidity not experienced for several hundreds of thousands of years. Of particular concern is that the rate of this change in ocean chemistry is about 100 times faster than at any other time over the past several million years. In addition 'ocean acidification is essentially irreversible during our lifetimes'[55,62,28] and would take tens of thousands of years to return to pre-industrial levels. The magnitude of projected changes in ocean chemistry can be estimated with a high level of confidence but the impacts on marine organisms and various geochemical processes are much less certain. The scale of changes may also vary regionally with the Southern Ocean most likely seeing the greatest changes in the short term. In addition, changes in ocean chemistry will result in interactions and feedbacks with the global carbon cycle, atmospheric chemistry and global climate – in ways that are currently not understood.

Increased $CO_2$ lowers oceanic pH, increases the amount of dissolved $CO_2$, reduces the concentration of carbonate ions and increases the concentration of bicarbonate ions. All of these changes will affect marine organisms and processes. Many marine organisms depend on current ocean chemistry to calcify, ie make shells, plates and skeletons. Calcification rates of several major groups of marine calcifying organisms, from both neritic and pelagic environments, will very likely decrease in response to changes in ocean carbonate chemistry. As well as corals, major groups of planktonic calcifiers likely to be affected include coccolithophora and foraminifera (calcite) and pteropods (aragonite).

Given the levels of uncertainties (primarily in terms of organism responses and interactions with other climate change variables), it is assumed that the ability of marine calcifying organisms (such as corals) to produce their skeletons will gradually decline over the 21st century, resulting in weaker and less robust skeletons (Hoegh-Guldberg et al. chapter 10). There is, however, little detailed information about high-resolution spatial patterns (eg cross-shelf) of change in ocean chemistry for the GBR. Recent studies demonstrate that the distribution of anthropogenic $CO_2$ in the oceans is not uniform[56]. As of 1995, aragonite saturation levels were considered optimal in the far northern GBR and adequate in the south. By 2040 the whole GBR will be marginal for coral reefs and, by 2100, the GBR will have low to extremely low aragonite saturation[28].

**Certainty:**
High that oceans have become and will be more acidic

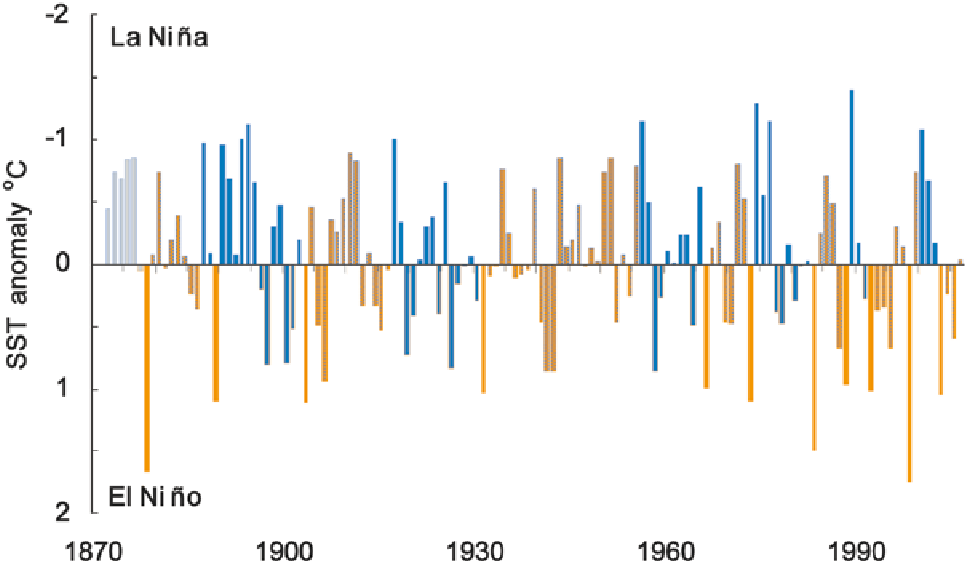
**Regional projection:**
Limited, generic 0.5 drop in pH by 2100

### 2.4.7 El-Niño Southern Oscillation

#### *Observed*

ENSO events (both El Niño and La Niña) are a significant source of inter-annual surface climate variability in northeast Queensland and the GBR. The instrumental ENSO record dating back to the late 19th century shows repeated occurrence of ENSO extremes. However there is no obvious trend toward more frequent El Niño or La Niña conditions (Figure 2.17). The 1997 to 1998 El Niño event is considered to be the strongest on record[40] and there is considerable debate as to whether this is evidence of changes in ENSO frequency and intensity that might be linked with climate change.

***Figure 2.17*** *Niño 3.4 May/April average sea surface temperature index of ENSO activity, 1872 to 2006 (axis inverted). Large positive values characterise El Niño events and large negative values characterise La Niña events. Most extreme (± 1 standard deviation) shown by filled bars. (Data source: HadISST, NOAA/NWS/NCEP Climate Diagnostics Bulletin[I])*



#### *Projected*

Although seasonal climate predictions of ENSO events are now reasonably reliable[40], projections of how ENSO will change with continued climate change are still unclear[23]. ENSO is the largest source of inter-annual climate variability in the instrumental climate record yet the relationship between ENSO and global warming is largely unknown. It is unclear whether enhanced greenhouse conditions will favour more El Niño or more La Niña-like conditions and/or changes in intensity and frequency of ENSO extremes[67]. This uncertainty also contributes to regional uncertainties as to how northeast Australia and GBR rainfall, river flow and tropical cyclones will change as climate change continues.

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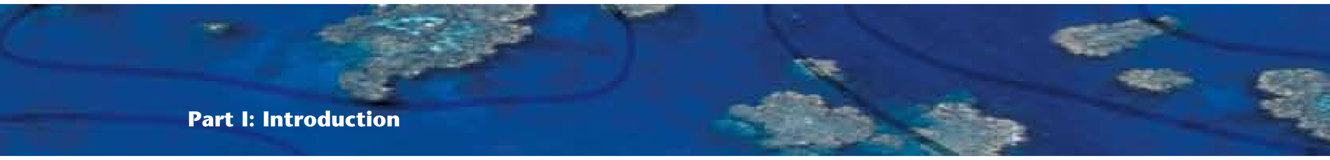
[I] http://www.cpc.noaa.gov/products/analysis_monitoring/bulletin/



In the absence of clear projections as to whether the occurrence, intensity and frequency of El Niño or La Niña events might change over the coming decades and century, it is assumed that ENSO events will continue to be a source of climate variability for this region and that this will be modulated by the Pacific Decadal Oscillation.

**Certainty:**
Low as to how ENSO frequency and intensity will change

**Regional projection:**
Likely to continue as a source of high inter-annual climate variability in northeast Australia and GBR region

### 2.4.8 Ultraviolet radiation

The stratospheric ozone layer protects life on Earth from the harmful effects of ultraviolet B (UVB) radiation. Human use of chlorine and bromine containing gases reduced the effectiveness of this layer leading to depletion of the ozone layer and the seasonal appearance of ozone holes over polar regions. Australia is particularly vulnerable given its close proximity to the Antarctic ozone hole. Although the Montreal Protocol (signed in 1987) has taken steps to stop ozone depletion, full recovery of the protective stratospheric ozone layer is not expected until at least 2020[25]. In addition, there may be an interactive effect with climate change as one of the consequences of global warming is a cooler stratosphere, which leads to further depletion of the ozone layer, just as it should be recovering. This is because a cooler stratosphere allows polar stratospheric clouds (which provide the necessary surface area for chlorine compounds to actively contribute to ozone loss) to form earlier and persist longer than usual. It, therefore, seems likely that harmful UVB levels may continue to increase with climate change[m]. Ultraviolet radiation receipt in tropical northern Australia is already extremely high due to its location close to the equator. A decrease in column ozone is associated with increased ultraviolet radiation. Such changes are, however, primarily limited to mid-latitude and polar regions with no significant trends observed in tropical regions[72]. Changes in ultraviolet radiation are not therefore, projected in the GBR region.

## 2.5 Non-linear and catastrophic changes

There are several potential non-linear and catastrophic changes that could occur as global climate continues to rapidly change ('climate surprises' and possible 'runaway greenhouse'). These potential 'wild cards'[13] include: a slowing or shutdown of the North Atlantic thermohaline circulation; more rapid sea level rise (order of several metres) due to disintegration of the Greenland and/or West Antarctic ice sheets; and the initiation of a runaway greenhouse effect as unanticipated feedbacks in the global climate system result in more rapid warming. Terrestrial carbon sinks are, for example, currently absorbing significant amounts of excess atmospheric carbon dioxide. If these sinks weaken or collapse, the Earth's climate system could be shifted to a new state of persistently higher greenhouse gas concentrations and higher mean temperatures[58]. These large-scale abrupt changes

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[m] http://www.ess-home.com/news/global-warming/ozone-depletion.asp

can be defined as 'dangerous climate change'. If such catastrophic changes occur, the consequences for the global community and ecosystems would be so great as to render any consideration of localised impacts trivial.

For northeast Queensland and the GBR, significant consequences would be expected from abrupt, unanticipated shifts in a) ENSO behaviour and b) Asian monsoon system. A significant shift towards more El Niño-like conditions would create significant problems for eastern Australia and be considered dangerous climate change[58].

## 2.6 Summary

The large-scale Australian summer monsoon and south-east trade wind circulations dominate the sub-tropical to tropical surface climate of northeast Australia and the GBR. The highly seasonal and highly variable inter-annual rainfall, river flows and occurrence of tropical cyclones are significantly modulated by global-scale ENSO events. These are in turn, modulated on decadal timescales by the Pacific Decadal Oscillation. Sea surface temperatures, air temperatures, rainfall and river flow tend to vary coherently across the region.

Surface climate is already showing evidence of significant changes due to the enhanced greenhouse effect with air and sea surface temperatures now significantly warmer than during the 19th and 20th centuries. The highly variable rainfall and river flow regimes do not currently show any evidence of significant changes towards either wetter or drier conditions. Although there appears to be a recent downward trend in the level of tropical cyclone frequency affecting the region, there is some indication of an increase in more intense tropical cyclones. Sea level is gradually rising.

Land and sea surface temperatures are projected to continue to warm and sea level is projected to continue to rise during the 21st century. These projections have a high degree of certainty. Globally, ocean chemistry has become more acidic and this is expected to increase during the 21st century. Key uncertainties exist in projecting what changes may occur to the highly variable rainfall and river flow regimes of the region. It is, however, highly likely that extreme dry years will be more extreme, due to higher temperatures, and that the intensity of individual rainfall events will increase, ie the rainfall and river flow regimes will become even more extreme than in the recent past. The intensity of tropical cyclones is likely to increase although there are no clear indications of changes in their occurrence and location. Another source of uncertainty relates to how ENSO events will change as the world continues to warm (Table 2.4). Changes in the frequency and intensity of extreme events (eg tropical cyclones, extreme rainfall and river flood events) and the rates of temperature changes are likely to be of critical ecological importance in the region as climate continues to change (chapters 5 to 22).

*Table 2.4 Summary of certainty and regional detail of projected changes*

| Variable | Certainty | Regional projection |
|---|---|---|
| Air temperature rise | High, already observed | Greater inland than along coast |
| SST rise | High, already observed | Greater in southern GBR and in winter |
| Rainfall and river flow | Low for changes in averages<br>High for more extremes | Similar spatial and inter-annual variability modulated by ENSO and PDO |
| Tropical cyclones | Low for location and frequency<br>High for increased intensity | Similar distribution but modulated by ENSO |
| Sea level rise | High, already observed and may accelerate | Limited, generic 0.1 to 0.9 m by 2100 |
| Ocean acidification | High, already observed drop in pH | Limited, generic 0.5 pH drop by 2100 |
| ENSO events | Low | Continued source of high inter-annual variability but modulated by PDO |

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## Appendix 2.1

## IPCC Special Report on Emissions Scenarios storylines (Nakicenovic and Swart 2000)

**A1 storyline** – describes a future world of very rapid economic growth, global population peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income.

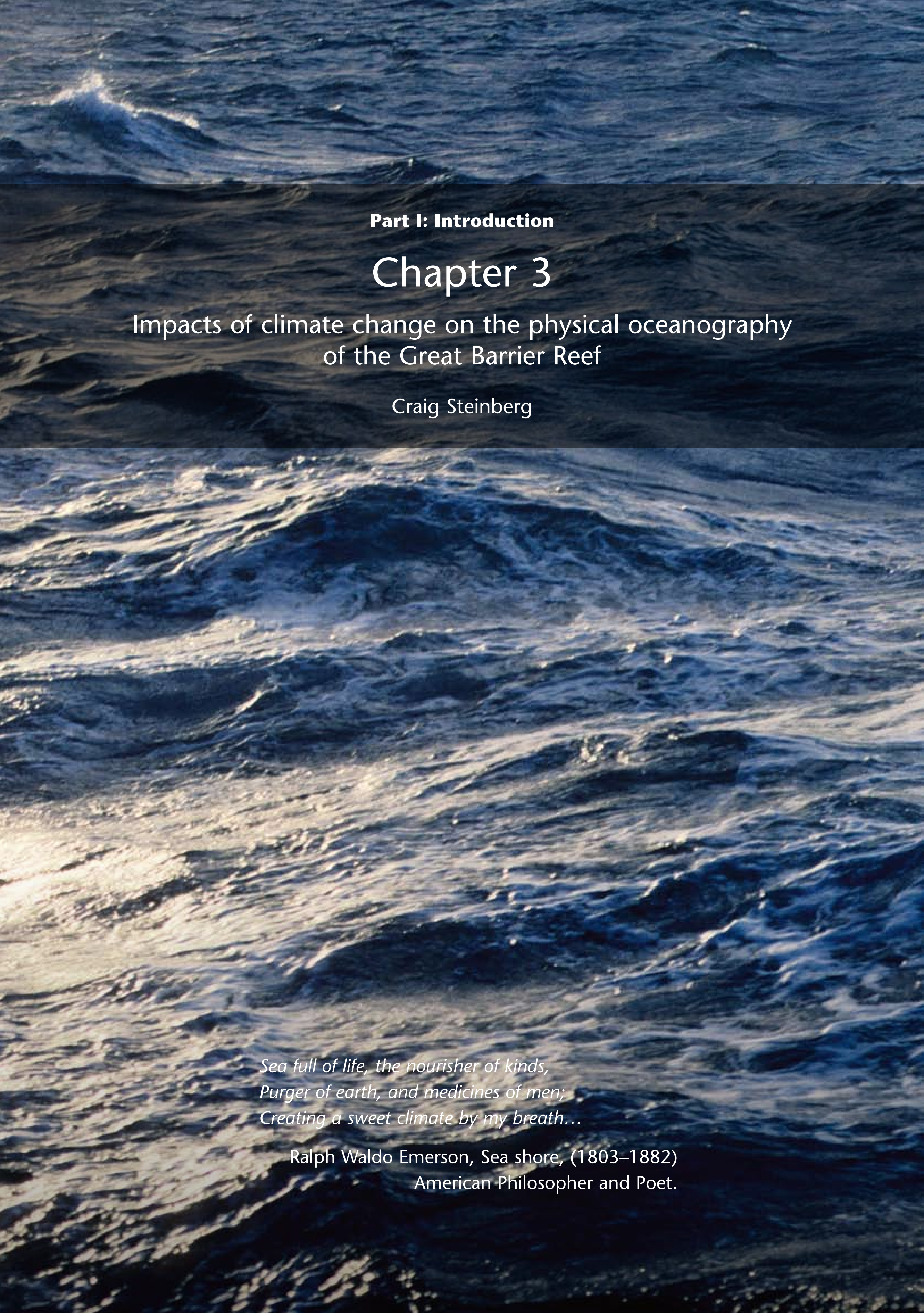
**A2 storyline** – describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally orientated and per capita economic growth and technological change are more fragmented and slower than in other storylines.

**B1 storyline** – describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures towards a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

**B2 storyline** – describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also orientated toward environmental protection and social equity, it focuses on local and regional levels.

***Table A1*** *Atmospheric concentration of carbon dioxide ($CO_2$ parts per million), global temperature rise (T°C) above 1961 to 1990 average, and sea level rise (SL cm) above 1961 to 1990 level for four SRES storylines for 2020s, 2050s and 2080s*

| | 2020s | | | 2050s | | | 2080s | | |
|---|---|---|---|---|---|---|---|---|---|
| | $CO_2$ | T | SL | $CO_2$ | T | SL | $CO_2$ | T | SL |
| **B1** | 421 | 0.6 | 7 | 479 | 0.9 | 13 | 532 | 1.2 | 19 |
| **B2** | 429 | 0.9 | 20 | 492 | 1.5 | 36 | 561 | 2.0 | 53 |
| **A1** | 448 | 1.0 | 21 | 555 | 1.8 | 39 | 646 | 2.3 | 58 |
| **A2** | 440 | 1.4 | 38 | 559 | 2.6 | 68 | 721 | 3.9 | 104 |



### Part I: Introduction

# Chapter 3

## Impacts of climate change on the physical oceanography of the Great Barrier Reef

Craig Steinberg

*Sea full of life, the nourisher of kinds,*
*Purger of earth, and medicines of men;*
*Creating a sweet climate by my breath…*

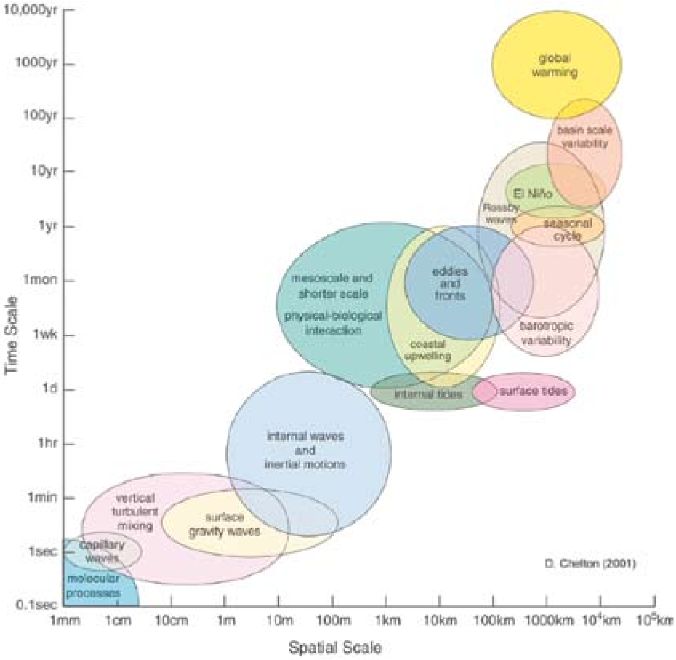
Ralph Waldo Emerson, Sea shore, (1803–1882)
American Philosopher and Poet.

## 3.1 Introduction

The oceans function as vast reservoirs of heat, the top three metres of the ocean alone stores all the equivalent heat energy contained within the atmosphere[29]. This is due to the high specific heat of water, which is a measure of the ability of matter to absorb heat. The ocean therefore has by far the largest heat capacity and hence energy retention capability of any other climate system component. Surface ocean currents (significantly forced by large scale winds) play a major role in redistributing the earth's heat energy around the globe by transporting it from the tropical regions poleward principally via western boundary currents such as the East Australian Current (EAC). These currents therefore have a major affect on maritime and continental weather and climate.

It is important to understand the temporal and spatial scales that influence ocean processes. Energy is imparted to the ocean by sun, wind and gravitational tides. The energy of the resulting large-scale motions is transmitted progressively to smaller and smaller scales of motion through to molecular vibrations where energy is finally dissipated as heat[42]. The oceans therefore play an important role in climate control and change, and Figure 3.1 shows the ranges of time and space, which characterise physical processes in the ocean and their hierarchical nature. Within this scheme, global warming occurs over different temporal (centuries to millennia) and spatial (global to hundreds of kilometres) scales. Through the energy cascade, climate change will affect all the other oceanic processes at smaller scales (summarised in Figure 3.1) and may alter their range, intensity and frequency and so strong regional variations in response are expected.

***Figure 3.1*** *Domain of space-time scales of physical processes (Reproduced courtesy of Chelton[17])*



Prior reviews of regional physical oceanography include Australian oceanographic processes in Church and Craig[21], Coral Sea circulation in Burrage[8] and the GBR in Pickard et al.[48]. For a more detailed review of physical processes on the GBR, Wolanski[62] is recommended. This chapter reviews the expected key climate-influenced oceanographic processes that affect the Great Barrier Reef (GBR). Section 3.2 explains how sea level variations are used to observe longer-term effects of climate change. Section 3.3 discusses processes involved in the air-sea heat budget that may result in a warming surface layer and the mixing mechanisms that are available in the water column to dissipate it. Section 3.4 provides a review of the current understanding of Coral Sea circulation. Section 3.5 discusses currents in the GBR. Finally, Section 3.6 discusses conclusions and recommendations. At the end of each sub section some effort is made to identify projected changes on the identified processes, assess their certainty and any regional detail if not already given in the previous chapter.

## 3.2 Observing long term climate changes: sea level and the El Niño-Southern Oscillation (ENSO)

The oceans remain the least understood and most sparsely sampled regions of the world due to the expense of sampling in marine environments and the historical reliance on slow ship based observations. Recent technological advances in observing networks, such as satellite remote sensing and Argo profiling drifters, is leading to a more global coverage and more frequently updated picture emerging. Long-term trends, however, remain difficult to recover due to the shortage of long-term records and the difficulty in separating out different signals from other processes. For example, one of the longest reliable instrument records available is sea level derived from coastal tide gauges. Sea level can be a good integrator of large-scale currents, temperature variability due to the expansion of seawater during warming and changes in meteorological forcing (eg setup due to wind stress).

Sea levels vary temporally and spatially over a wide range of scales. Surface gravity waves generated by storms attain heights on the order of 10 metres and storm surges can pile water up on the coast and may subsequently propagate along the coast as trapped waves. Tide fluctuations in sea level can range up to 10 metres depending on location. Large-scale currents can cause sea level fluctuations of up to one metre. Annual variability in sea level is principally due to seasonal warming and thermal expansion of the water column, variations in prevailing wind strength and direction and changes in the strength and timing of the gravitational tide.

To effectively reveal long-term (eg inter-annual and inter-decadal) sea level changes associated with climate change, long-term records are assessed after shorter term seasonal and shorter period variability is removed. This is achieved by subtracting the predicted tide and smoothing out these higher frequency processes by filtering. Correction must also be made for tectonic movement and crustal deformation caused by the loading of flooding tides on continental shelves. The National Tide Centre at the Bureau of Meteorology is responsible for observing long-term sea levels in Australia through the Australian Baseline Sea Level Monitoring Project, and throughout the South Pacific, through the South Pacific Sea Level and Climate Monitoring Project. Long-term sea level trends on the GBR show an increase of 2.9 mm per year since 1991 at Cape Ferguson (central GBR) and a 2.6 mm per year increase since 1992 at Rosslyn Bay (southern GBR). Based on satellite altimetry, Church et al.[23] calculated an average sea level rise in the Indian Pacific region for the period 1993 to 2001 to be 4 mm per year. Uncertainty in the accuracy of these trends is caused by variability associated with global-scale phenomena like ENSO, and the relative shortness of high precision records from satellite altimetry and the tide gauge network.

Sea level anomalies with the predicted tides, seasonal cycles and linear trend removed are shown in Figure 3.2 for Rosslyn Bay and Cape Ferguson. Both show that during the 1997–1998 El Niño event, sea levels rose approximately 18 cm over a 12 month period revealing a regional-scale variation two orders of magnitude larger than the long term sea level rise. The West Pacific Warm Pool (WPWP), in the seas around northern Papua New Guinea and the Solomon Islands, exhibited a change in sea level of more than twice that observed in the GBR at 40 cm (Figure 3.3).

**Figure 3.2** *Sea level anomalies for Cape Ferguson and Rosslyn Bay. Units are in metres (Adapted from the Australian Baseline Sea Level Monitoring Project, Annual Sea Level Data Summary Report July 2004 to June 2005[a])*

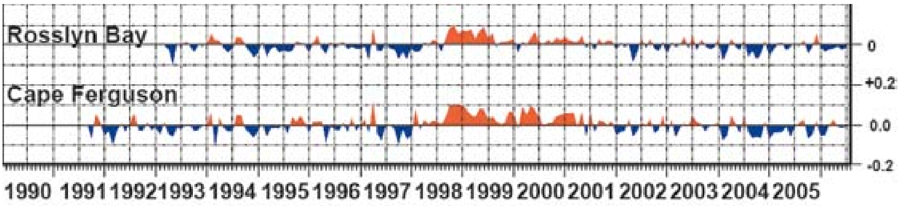
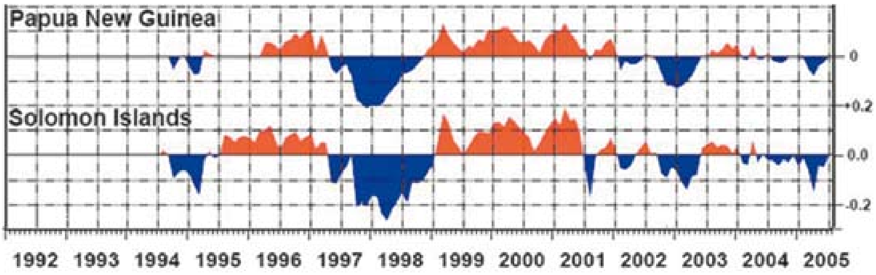


**Figure 3.3:** *Sea level anomalies observed by the Manus Island, PNG and Honiara, Solomon Islands sea level gauge (Adapted from Pacific Country Report, Sea Level and Climate: Their present state, Papua New Guinea, June 2005[b])*



The three to seven year ENSO cycle affects sea level through a complex interaction between atmospheric and oceanographic processes. ENSO was originally observed as a change in the difference in atmospheric pressure between Darwin and Tahiti[5]. This difference provided a simple indicator of the shifting atmospheric Walker circulation in which lower pressures occur where air rises over warm ocean waters and higher pressures occur where air descends over cooler waters. Figure 3.4 shows that during the opposite ENSO phase, La Niña, the WPWP (centred north of Papua New

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[a] http://www.bom.gov.au/oceanography/projects/abslmp/abslmp.shtml

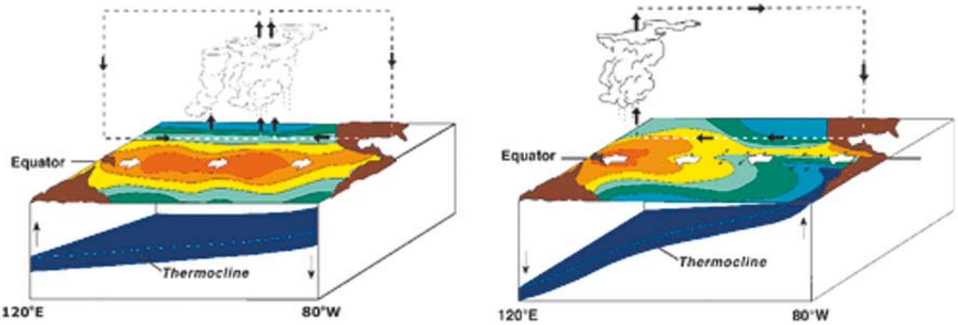
[b] http://www.bom.gov.au/oceanography/projects/spslcmp/spslcmp.shtml

Guinea) warms the equatorial air causing it to rise, and thereby lowering the atmospheric pressure at Darwin. At the same time, the eastern Pacific experiences characteristically cooler upwelled waters from the divergence of surface waters away from the South American continent due to the local winds and the equatorward transport of cooler waters by the Peru Current from the south. Air subsides in the eastern Pacific to complete the convection cell and increases the air pressure at Tahiti. During the El Niño phase of the Southern Oscillation the reverse occurs. As the heat anomaly moves eastward the warmer waters form a low-density cap, which prevents upwelling and the cooling of waters off the coast of Peru. Sea levels in the warmer regions are higher due to a combination of thermal expansion and a convergence of currents causing the ocean surface to dome up.

There is also a deepening of the surface warm, low-density layer. The region of transition between the warmer surface waters and colder deep oceanic water is known as the thermocline. This is displaced lower due to the build up of the warmer waters[70]. Thus during La Niña the eastern Pacific experiences cold water upwelling (with the thermocline breaking the surface), and the Western Equatorial Pacific experiences a depressed thermocline that hinders any upwelling due to the cooler water being much deeper. In contrast, during El Niño, the thermocline is much closer to the surface in the Western Pacific making the cooler waters potentially more available to continental shelves. It is important to note that whilst the sea level may vary by tens of centimetres, thermocline depth can vary over a range of hundreds of metres, typically occurring between 50 and 200 metres depth during ENSO. This effect arises because of the relatively small density contrast between the internal layers that make up the thermocline and the huge density difference between the ocean and the atmosphere. Actual thermocline response along the GBR by ENSO is unknown and may not necessarily occur south of the WPWP, however it can be inferred from the sea level anomaly data that there should be a response. There is an El Niño related sea level increase of 10 cm that can be seen as far south as South Australia. Here the thermocline has been observed to shallow to 60 to 120 metres, 150 metres above the mean thermocline depth[46]. This signal however is thought to propagate from the Indo-Pacific WPWP via the Indo-Pacific throughflow and along the shelf edge wave guide from Western Australia to South Australia, not along the east coast[25].

The extreme 1997–1998 ENSO event (the largest on record) is likely to have been exacerbated by an in-phase Pacific Decadal Oscillation (PDO) (see Lough chapter 2) that behaves in a similar manner to ENSO in the Western Pacific. Over the last few decades, considerable effort has been put into explaining and predicting regional ENSO affects. With each event there are significant variations in behaviour and

***Figure 3.4*** *Schematic of the two phases of the El Niño Southern Oscillation during a La Niña (left) and El Niño (right) phase (Schematic courtesy of NOAA/ PMEL/TAO)*



hypotheses are refined. Whilst progress has been made in predicting the onset of El Niño, more recent studies are looking at the longer-term modulation of ENSO and different triggering mechanisms observed by ocean observing systems[59].

The 1997–1998 ENSO event shows that changes in currents, transport of warmer waters and thermocline displacement are likely to cause significant impacts on the GBR. Currents are highly variable on a whole range of scales and accurate long-term measurements are limited. Sea level has therefore been the traditional indicator of large-scale oceanographic changes. However the sea level signal can also be from thermal expansion (if warming) and not just from changes associated with changes in the strength and direction of major currents.

## 3.3 Thermal stratification and mixing of the water column

Section 3.2 discussed the importance of thermocline depth changes for regulating the appearance of cool, nutrient rich oceanic waters at the surface. This section will explore how ocean warming forms a buoyant surface layer and how mixing can disperse the heat throughout the water column.

Incoming solar radiation varies naturally by a few tenths of a percent due to dark sunspots and the 11-year solar cycle. Whilst these changes are small, they do influence climate variability. Increases in greenhouse gas concentrations are changing the Earth's atmospheric composition and radiative balance. In response, the Earth system is absorbing excess heat and the global oceans in particular are taking up much of this excess. The amount of radiation incident at the ocean surface depends upon the amount of cloud cover, aerosols, water vapour, angle of incidence, reflection and scattering. Short-wave radiation spectra are comprised of far infrared, visible and ultra-violet radiation. Absorption varies according to the wavelength, with the longer infrared being absorbed in the first few centimetres of surface waters and ultra-violet radiation penetrating to hundreds of metres into the ocean. However, the greatest amount of warming occurs near the surface because 75 percent of the total short-wave energy is absorbed in the top 5 metres[42].

Fluxes across the air-sea interface include the incoming and outgoing short and long wave radiation, sensible and latent heat fluxes. The tropical oceans tend to have a net gain of heat over the year although cold air temperatures, wind, evaporation and night time back radiation can cause periods of heat loss. The surface heating stabilises the top layer due to thermal expansion of the water reducing its density. Winds are the major source of turbulence that can mix these waters further down into the water column. The depth to which they can mix is dependent on the strength of wind, so over a warming period numerous thermal layers can develop that are progressively mixed deeper in the water column by successively stronger wind events.

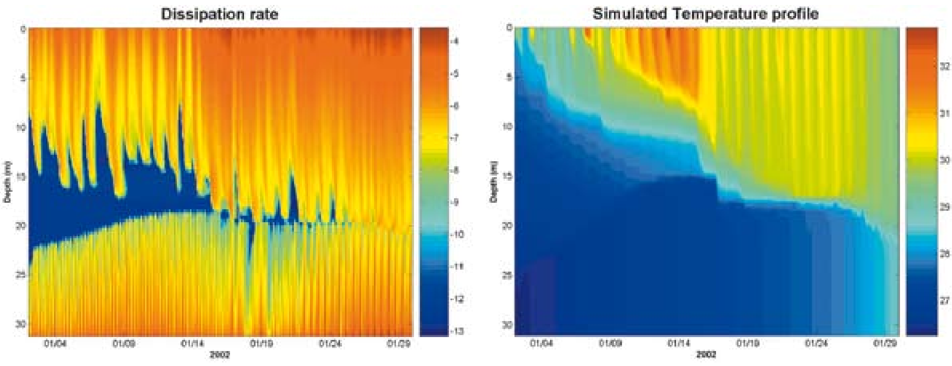
In the tropical ocean this well-mixed surface layer can extend down to depths exceeding 100 metres and this depth usually defines the location of the main thermocline for surface waters. Deeper mixing or additional thermocline deepening occurs through surface water convergence, entrainment driven by larger turbulent eddies or current shear instabilities[36] and basin-scale tilting. The GBR shelf is considered to be well mixed during most of the year assisted by the strong southeast trades[21] however an important exception occurs during summer warming events. Whilst the summer stratification may be considered weak compared with more temperate regions, the fact that corals are living at the limit of their thermal tolerances means that these episodes have a higher ecological importance than would otherwise be the case.

Figure 3.5 illustrates the wind-generated turbulence through the water column over the course of one month during summer as indicated by the turbulent energy dissipation rate in the panel. The winds vary in strength diurnally but mix to a depth of between 10 and 20 metres over the course of the month. The panel shows how temperature response to the mixing is controlled by daily heating and a prolonged warming period from 9 to 15 January 2002. This warm surface layer is progressively mixed down to about eight metres, eventually overcoming the increased stability of the buoyancy from the lower density warmer waters. When the winds strengthen mid-month, the heat extends deeper to over 20 metres depth during the remainder of the month. The result is that the high surface temperatures are gradually redistributed into deeper layers. In tandem, the winds also cool the surface waters by releasing latent heat to the atmosphere through evaporation. Other factors contributing to cooling surface waters include cloud cover, which reduces direct heating by insolation during the day and clear skies at night enabling long wave radiation to escape the atmosphere.

On the GBR shelf, additional energy for vertical mixing from the sea floor up through the water column is sourced from currents that are dominated by the tides (Figure 3.5). Tidal currents generate turbulence from the shear produced by friction at the sea floor. A persistent cool bottom boundary layer exists in this case. Where tides are stronger and/or the water depth is shallower, they can mix all the way to the surface and this is a common feature along coasts, in channels between reefs and in macro-tidal areas. In deeper regions, where the surface wind mixing doesn't overlap with the tidal mixing from the sea floor, a central core can result, exhibiting a reduced dissipation rate where there is negligible turbulence available for mixing, as seen in the first half of the month in Figure 3.5.

Figure 3.6 shows two satellite images of sea surface temperatures for the GBR and Coral Sea. Persistent summer cooler waters are found along the outer far northern GBR during the austral summer in December and January. Hotter waters are apparent on the reef tops of large mid-shelf reefs (especially off Princess Charlotte Bay located at 14° S) and in the shallow waters along the coast. In contrast, waters are 2°C cooler along the outer edge of the continental shelf where the Ribbon Reefs occupy over 90 percent of the shelf break. It is thought that intrusions from a variety of processes (see section 3.4) cause cooler, deeper water to encroach onto the outer shelf, mixing waters around

***Figure 3.5*** *Simulated profile of the time history of turbulent energy dissipation rate (top) and temperature (bottom) for a midshelf location on the central GBR in January 2002*



the coral reefs[53]. These mechanisms effectively provide a microclimate for the outer reef corals keeping them cooler and less susceptible to heat stress than their mid-shelf counterparts. Figure 3.7 shows average December sea surface temperatures for the central and southern GBR. The dense outer reef matrix between latitudes 19° and 23° experiences consistently lower temperatures than the coastal and largely reef-free lagoon that extends to the middle of the shelf.

***Figure 3.6*** *December (left) and January (right) sea surface temperature climatology of the northern and far northern GBR, averaged from 1990 to 2000 (Source: Skirving et al.[54])*

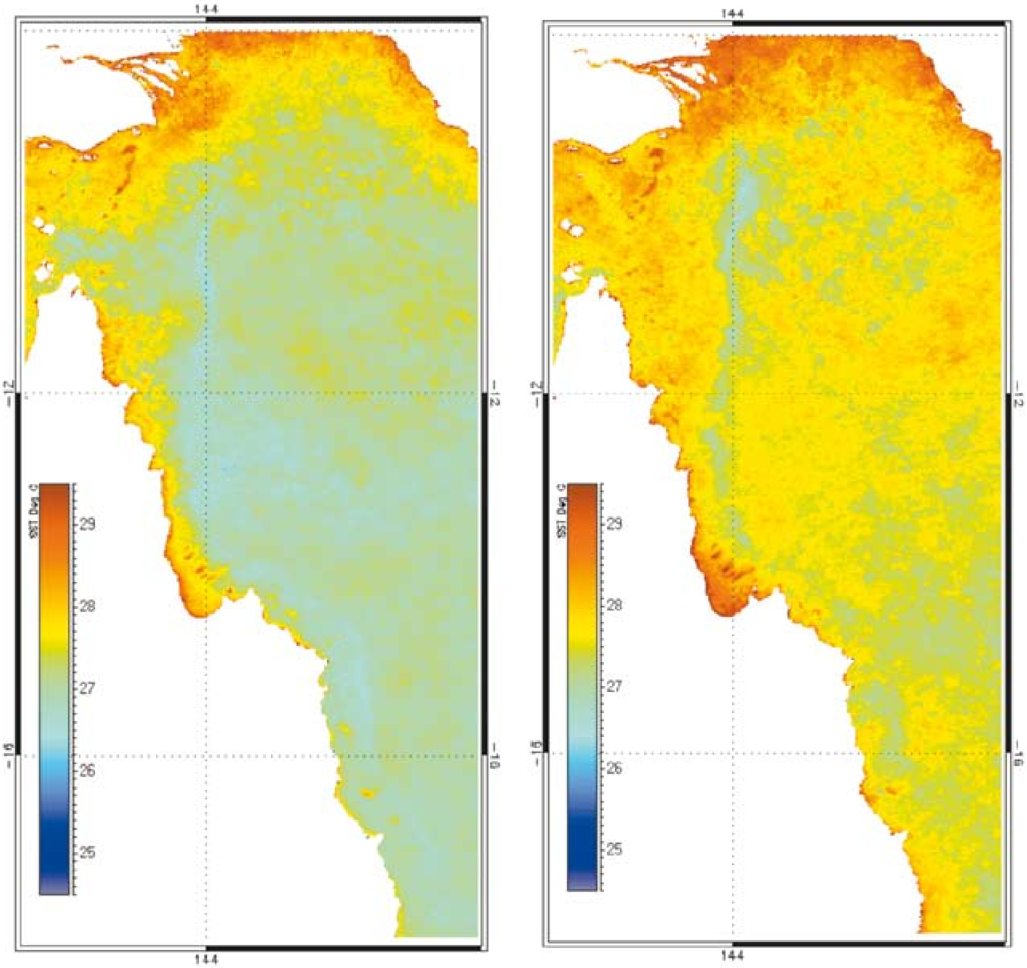
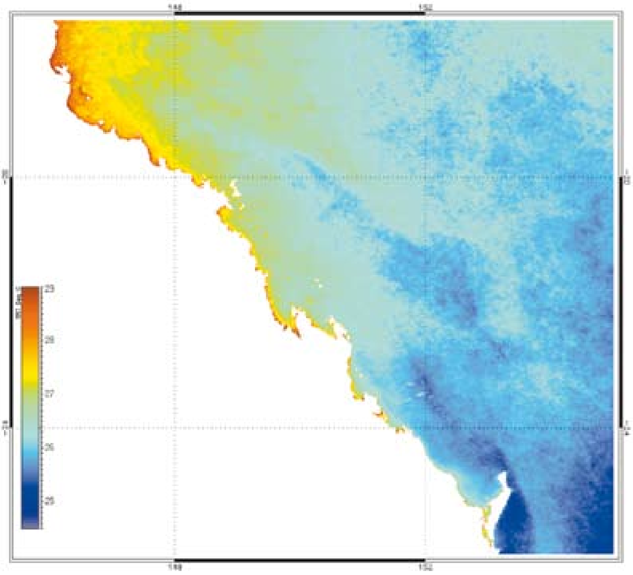


***Figure 3.7*** *December sea surface temperature climatology of the central and southern GBR averaged from 1990 to 2000 (Source: Skirving et al.[54])*



The oceanic surface mixed layer mediates the exchange of mass, momentum, energy, heat and dissolved gases between the atmosphere and the ocean, and hence plays a central role in determining long-term climate response[36]. In tropical waters the surface layer tends to be oligotrophic and so any deepening of the mixed layer can potentially provide a source of nutrients to the photic zone, enabling an increase in primary productivity and cooling of surface waters. Thus deep chlorophyll maxima are widespread in the open ocean near the thermocline. Since heating is stabilising, it tends to suppress the penetration of turbulence down into the water column so mixing will be confined to a shallower surface layer. Climate modelling predicts that this may suppress the upward flux of nutrients reducing oceanic primary productivity, but also induce oscillations and increased variability in the amount of phytoplankton in the deep chlorophyll maximum and export of carbon into the ocean interior[34]. Momentum imparted to the more stable, shallower surface layer by the wind may speed up surface currents as the majority of the energy transfer will be confined to this layer.

**Projected:**
Thermal stratification is to increase. Depth of thermocline to rise and surface layer currents to increase.

**Certainty:**
High-significant warming already observed and projected to continue. Medium – Thermocline depth response

**Regional detail:**
Oceanic thermocline likely to shallow, stratified regions on the GBR shelf to increase in areas with less energetic tides.

## 3.4 Coral Sea inflows

### 3.4.1 South Equatorial Current

The South Equatorial Current (SEC) primarily drives Coral Sea circulation. It is the northern arm of the ocean basin scale South Pacific Gyre. The gyre is driven by the latitudinal contrast of the strong westerly winds forming the eastward flowing circumpolar current in the Southern Ocean and the south-easterly trade winds in the lower latitudes forcing the westward flow of the SEC. The surface waters of the SEC are warmed by several degrees as they traverse the equatorial Pacific and form a well-mixed surface layer of around 150 metres in thickness[16].

The classical view of Coral Sea circulation is derived from ship based hydrographic observations[52,19,2] and early, low resolution numerical modelling[33]. This view has the broad SEC entering the Coral Sea from the east and bifurcating at the GBR into a northern arm, the North Queensland Current or Hiri Current and the poleward flowing East Australian Current (EAC). The location of the bifurcation varies seasonally between 14° S and 20° S and lies at the southern end of this range during the southeast trade wind season (April to November). Underlying the EAC is a permanent undercurrent that flows northwards and eventually joins up with the Hiri Current[20,19,33,8].

Over the last two decades technological advances in computing, satellite and acoustic remote sensing and ship positioning has revealed significant complexity and detail in ocean circulation. Webb[60] used a numerical model to suggest that the broad westward SEC inflow is broken up into a number of zonal jets by shallow bathymetry associated with island archipelagos. The reef systems effectively impede the flow and force the waters around them. Figure 3.8 is a schematic showing that jets form north and south of Fiji[56], Vanuatu and New Caledonia. More recently, Ridgway and Dunn[49] have been able to discern these features in climatological data with recent increased resolution and after allowing for bathymetric control. Once in the Coral Sea, currents deviate around the reef systems on the Bellona (west of New Caledonia), Queensland and Marion Plateaus. This topography produces multiple pathways for the SEC to reach the GBR. Once the jets encounter the Australian continental shelf they form the EAC and Hiri currents flowing along the western boundaries. Kessler and Gourdeau[38] found evidence that jets can also be caused by quasi-permanent structures in the wind field, independent of the island and reef systems.

Figure 3.9 shows a snapshot of an eddy resolving ocean circulation model[51] showing the complexity of the Coral Sea circulation. It contains most of the features mentioned above as well as significant meanderings of the current flow. A large recirculation of the Hiri Current, known as the Papuan Gyre, provides a pathway from Papua New Guinea waters back to the far northern GBR[8]. A smaller recirculation is seen off the southern GBR, south of the Swain Reefs and east of the Capricorn Bunker Group. The model also reproduces the transient zonal jets extending eastward from southern end of the GBR (off Fraser Island), which were first detected using sea surface temperature imagery[11,12].

The SEC and EAC strengthen during an El Niño when the southern WPWP moves eastwards along the equator to the central Pacific. This is due to the SEC being displaced south[69,43,35], which favours EAC flow rather than contributing to the Hiri current. Burrage et al.[10] found a strengthening of the EAC in the central GBR and Wolanski and Pickard[66] speculate that ENSO may account for anomalous currents in their data during the 1982–1983 El Niño.

***Figure 3.8*** *Southern Equatorial Current (SEC) pathways to the Coral Sea: North Fiji Jet (NFJ), South Fiji Jet (SFJ), North Vanuatu Jet (NVJ), South Vanuatu Jet (SVJ), North Caledonia Jet (NCJ), South Caledonia Jet (SCJ). Once the streams approach the GBR the flow bifurcates to form the East Australian Current (EAC) and a northern arm, called the Hiri Current or North Queensland Current. This branch then feeds the New Guinea Coastal Current (NGCC) that feeds the West Pacific warm pool and is a source for the Equatorial Under Current (EUC). The currents in orange indicate major seasonal changes during the NW Monsoon. The NGCC reverses and the Southern Equatorial Counter Current (SECC) reverses the SEC nearest the equator. (Adapted figure prepared by SPICE*[c]*, with alterations by the author for flows in the Coral, Solomon and Bismarck Seas)*

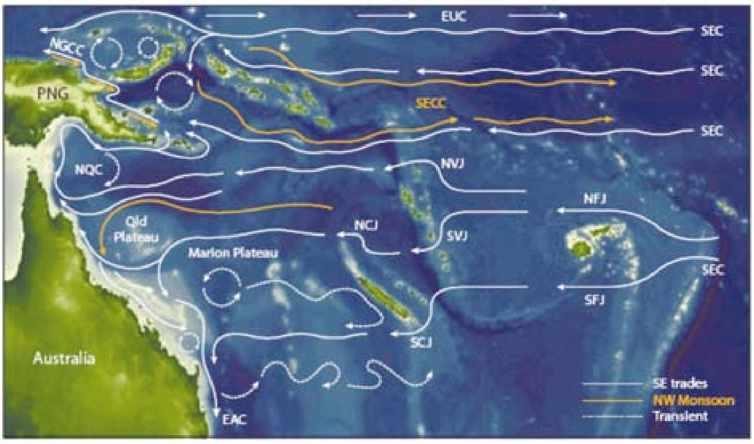
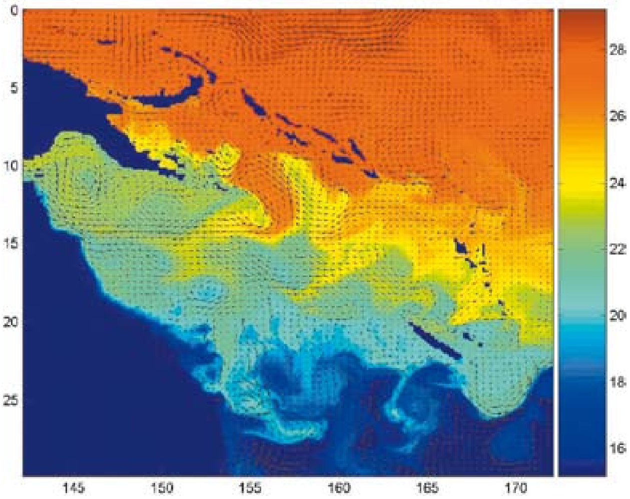


***Figure 3.9*** *Snapshot of the surface circulation of the Coral Sea from the OFAM model (run spinup4) for 27 February 2002. Arrows indicate current strength and direction, the background colour indicates model temperatures (model data courtesy Bluelink*[d]*)*



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[c] http://www.ird.nc/UR65/SPICE/

[d] http://www.cmar.csiro.au/bluelink

**Projected:**
Climate modelling by Cai et al.[15] found that the southern EAC will strengthen in the Tasman Sea due to the Southern Annular Mode causing lighter mid latitude winds and stronger southern ocean westerlies. Observations by Roemmich et al.[50], who analysed 10 years of Argo floats and satellite altimetry, have found that the South Pacific Gyre has spun up over the last decade due to increased southeast trade winds, although it appears to be subsiding in recent years.

**Certainty:**
Low – Medium

**Regional detail:**
The variations in the strength and breadth of the SEC are critical to understand given that it is the main driver of the Coral Sea circulation. Whilst the SEC shows only a small seasonal variation, the relative contributions of the various zonal jets entering the Coral Sea will vary the location of the bifurcation and hence the relative strengths of the EAC and Hiri current.

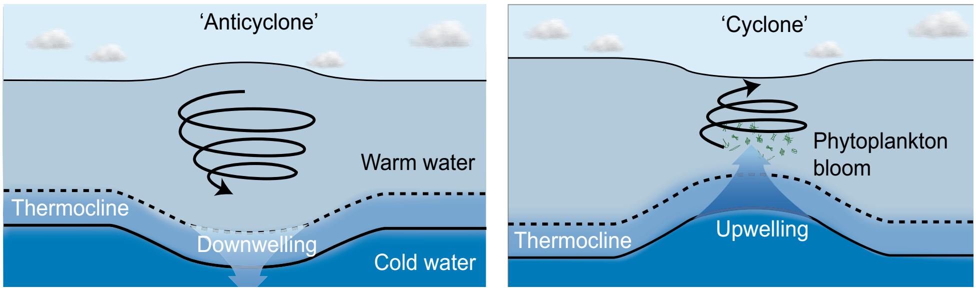
### 3.4.2 Eddies

The majority of kinetic energy in the ocean resides not in the steady ocean basin gyres but in eddies. These eddies are embedded in the larger scale currents and are therefore a large source of current variability in the ocean[37]. Eddies can be formed by a number of mechanisms, including baroclinic flow instabilities in the wake of islands or variations in wind fields. Energetic currents often become hydrodynamically unstable, creating meanders, which eventually shed eddies. These isolated eddies can last for years and can be transported with the prevailing flow of the major current systems. For example, in the Tasman Sea the EAC forms a meander and anticyclonic eddies pinch off from the main current moving south past Tasmania[24]. Stammer et al.[55] have mapped the global occurrence of eddies from over a decade of satellite altimeter data and have found that there has been a general decline in activity in the Western Pacific Ocean but an increase to the east of Australia. This coincides with the area of the most rapid warming in the ocean[61]. Thus any change in the intensity of the EAC upstream, in the Coral Sea is considered to be a factor leading to the warming. Eddies in the Coral Sea are found to have an annual cycle with a maximum in the austral summer and minimum in winter, with a period of 70 to 80 days.

Eddies have cyclonic (clockwise in the Southern Hemisphere) or anticyclonic (anticlockwise) senses of rotation. An analogous system can be found in atmospheric circulation around high and low air pressure systems. For example, weather charts show anticlockwise movement of air around a central high pressure. In both cases, higher pressure or sea level lies to the left of the direction of flow in the Southern Hemisphere due to the pressure gradient forces balancing the Coriolis force. Figure 3.10 shows a cross-section of oceanic eddies. The anticyclonic eddy has a convex surface with higher sea level at the centre whereas a cyclonic eddy is characterised by a concave surface with lower sea level at the centre. The anticyclonic eddies have warm cores due to the convergence of warmer surface waters at the centre which deepens the thermocline. In contrast, cyclonic eddies are characterised by a cold core due to the divergence of surface water allowing the thermocline to dome upwards. This can allow increased local productivity by bringing nutrient rich water into the euphotic layer. These eddies can often be seen in sea surface temperature[12] and ocean colour imagery of the Coral Sea.

Figure 3.11 shows a cyclonic eddy (with a chlorophyll-a signature in the centre) on the shelf edge near Hydrographers Passage, east of Mackay. The ocean circulation model (Figure 3.9) also shows a cold core eddy embedded in the flow east of the GBR at about 18° S.

***Figure 3.10*** *Cross section of an anticyclonic (left) and cyclonic (right) rotating eddy showing the respective convex and concave displacements of the sea surface and thermocline*



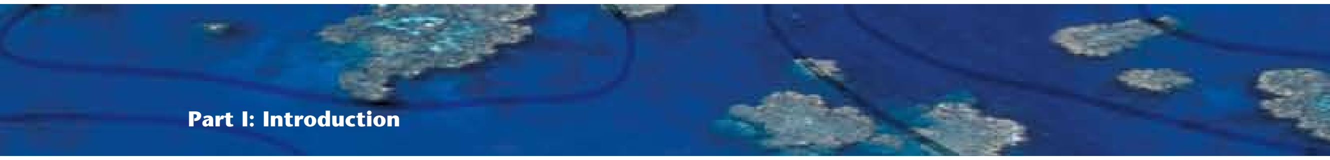
**Projected:**
With any increase in the SEC, eddy activity is also expected to increase. Perturbations to thermocline are likely to increase in magnitude.

**Certainty:**
Medium

**Regional detail:**
Eddies expected to form with increasing frequency from the same topographic features that generate them however other mechanisms are also at play. Eddies impacting on the GBR can also affect the location of the bifurcation between the EAC and Hiri currents.

### 3.4.3 Rossby waves

Another source of variability are Rossby waves. These are formed from the transient adjustment of ocean circulation to changes in wind and thermal forcing at the sea surface[18]. They can propagate westwards at less than 10 cm/s and can take months to decades to traverse the Pacific Ocean. They propagate fastest near the equator and are slower at higher latitudes. Whilst they have small surface amplitudes of about 5 cm, the thermocline can be displaced by over 50 metres, and impact shelf edge mixing and transport along the GBR. Due to their small amplitudes, they have only recently been able to be detected from satellite altimetry although the theory of their existence is well established[29].



**Projected:**
Rossby wave activity is expected to increase, perturbations to thermocline are likely to increase in magnitude.

**Certainty:**
Low – Medium

**Regional detail:**
Westward propagating waves are not expected to speed up, however, their amplitudes may increase. Their propagation in to the Coral Sea is complicated by topographic barriers and so regional effects are uncertain.

## 3.5 Great Barrier Reef currents

Inside the reef matrix there is a complex circulation due to the interaction of currents from tide, wind, continental shelf waves, inflows from the SEC and the physical barrier of the reefs themselves. The following sections describe the major characteristics of these flows along the GBR.

### 3.5.1 Bathymetry

The topographic complexity of the GBR significantly influences circulation and mixing on the shelf. The continental shelf in the far northern and northern GBR is a relatively narrow 50 to 70 km for most of its length with the exception of Princess Charlotte Bay located at latitude 14° S and toward Torres Strait at 10° S where it widens to over 150 km. The shelf is relatively shallow, gradually deepening to 40 to 60 metres toward the shelf edge. In the central region the shelf gradually widens from 18° S to about 110 km and sloping to a depth of around 100 metres. The GBR is widest in the southern region at latitude 21° S, near Broad Sound at around 250 km. There is a sudden narrowing south of the Swains in the southern region to approximately 60 km width where the outer shelf reverts to a relatively shallow 40 to 50 metres. The Capricorn channel at a depth of 90 metres extends from the southeast where the shelf narrows just south of the Swains, forming a trough in the lagoon separating the inner and the outer half of the shelf where there Swains and Pompey reef complexes are situated.

The Great Barrier Reef lives up to its name in the far northern and northern regions where long 'ribbon' reefs are oriented along the shelf, and in the southern region where the outer half of the wide shelf is occupied by a 'barrier' reef matrix. The reefs cover over 90 percent of the outer shelf leaving only narrow channels for oceanic and tidal flows to pass[48,67]. The central region is characterised by a more open reef matrix and together with a change in orientation of the shelf from north to south to a south-easterly orientation at a latitude around 19° S, allows the southward flowing EAC to penetrate directly into the GBR lagoon[7]. To a lesser extent, passages in the northern GBR allow Coral Sea water to flow through Trinity and Grafton passages, offshore from Port Douglas and Cairns. In this region the Ribbon Reefs give way to a less dense reef matrix to the south.

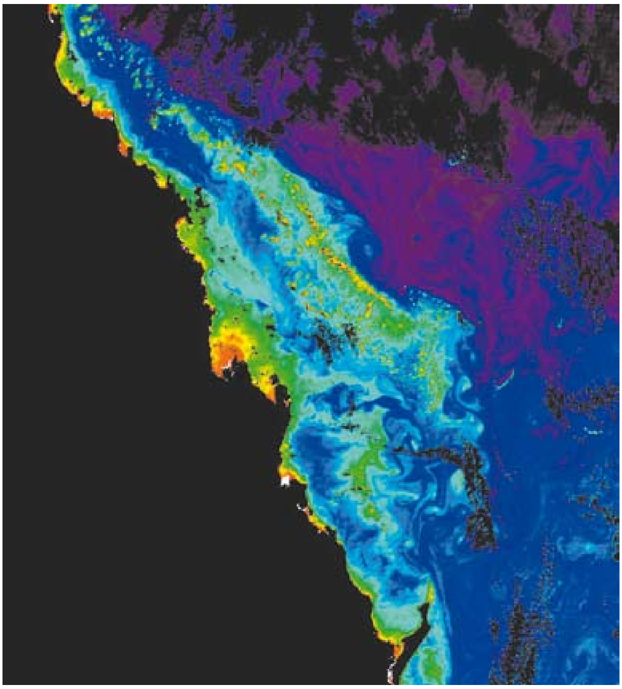
### 3.5.2 Western Boundary Currents: EAC and Hiri Current

The southward surface flow of the EAC in the central GBR peaks in November to December and is at a minimum in April to May due to the opposing southeast trade winds[9]. The EAC however is not considered fully developed until it reaches a latitude of 26° S where the rest of the branches of the SEC, such as the South Caledonia Jet converge at the Queensland continental shelf and contribute to the EAC.

The Hiri current[33] is an equatorward low-latitude western boundary current and is fully developed north of 14° S. It is guided by topography around the perimeter of the Gulf of Papua and the majority eventually flows around the Louisiade Archipelago to the Papua New Guinea northern coast in the Solomon Sea. The Louisiade Archipelago is an extension of the shelf islands and reefs from the southeast of Papua New Guinea. Some of the Hiri current recirculates as the Papua Gyre back to the far northern GBR[57,2,8].

These major current systems also drive along-shelf flows on the continental shelf that remain in geostrophic balance and so are principally driven by cross-shelf sea level gradients setup by the currents[9,10,62]. The lagoonal branch of the EAC can often be tracked as a southeastward extending low chlorophyll tongue of oceanic water in satellite ocean colour imagery (Figure 3.11) eventually moving out through the Capricorn Channel in the southern GBR.

***Figure 3.11*** *MODIS Chlorophyll-a image of the central and southern GBR showing oceanic (blue) water intruding through Palm Passage and toward Capricorn Channel. Red is high Chlorophyll-a or turbid water; blue is low Chlorophyll -a water; and black is land and cloud (Image courtesy of AIMS Remote Sensing)*



The sea level and geostrophic pressure gradients set up by the currents also cause the thermocline to mirror these movements. As higher sea levels are found to the left of the geostrophic current flow in the Southern Hemisphere, the thermocline will fall. Thus a strong Hiri current depresses the thermocline and suppresses the ability of cooler deep waters to access the continental shelf, whereas the opposite is true for the poleward flowing EAC. The thermocline rises and sea level lowers along the continental shelf. Furnas and Mitchell{27} found that primary productivity is at a maximum at 21° S off the Swains and Pompey group of reefs where the EAC is well formed and large tides can force a current across the continental slope and shelf (Figure 3.12) assisting the delivery of deeper oceanic waters to the shelf and mixing to the surface. The pulsing of these currents therefore generates significant variations in the thermocline depth and control over any shelf margin intrusions into the GBR.

In the Capricorn Bunker Group of the southern GBR, the circulation along the continental shelf margin is dominated by the meandering EAC. The sudden narrowing of the shelf south of the Swains reefs allows the current to meander and regularly produces a clockwise gyre with a mean northwest flow on the outer shelf[31,12]. Figure 3.13 shows the warm EAC seaward of the Swains reefs heading south and turning northwest just north of Fraser Island. It can be seen entraining Capricorn Channel waters from the lagoonal branch of the EAC into the cyclonic gyre. A shelf break front can be seen which separates the oceanic and shelf waters. When the recirculation is strong, the thermocline will be lowered, suppressing upwelling along the shelf break and forcing warmer surface Coral Sea waters past the Capricorn Bunker Group of reefs.

**Projected:**
The EAC and Hiri currents are expected to increase in strength due to direct forcing from the SEC. Central GBR currents may weaken and reverse if the bifurcation moves south.

**Certainty:**
Medium – Modulations from ENSO and PDO will be significant.

**Regional detail:**
Location of bifurcation is likely to move according to the large-scale wind stress curl driving the SEC. Whether one current strengthens at the expense of the other remains uncertain.

***Figure 3.12*** *Cross section, looking north, of the boundary currents showing thermocline adjustment for accelerating currents: the northward flowing Hiri current (left) has sea levels rising along the GBR and coast and the thermocline deepening. The EAC (right) shows sea levels dropping at the coast and the thermocline rises allowing waters to upwell onto the shelf.*

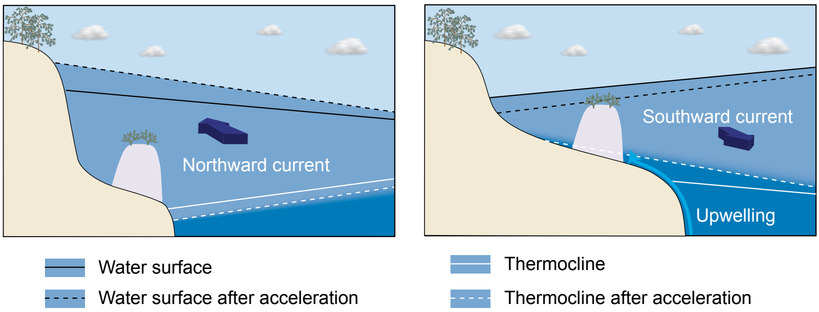
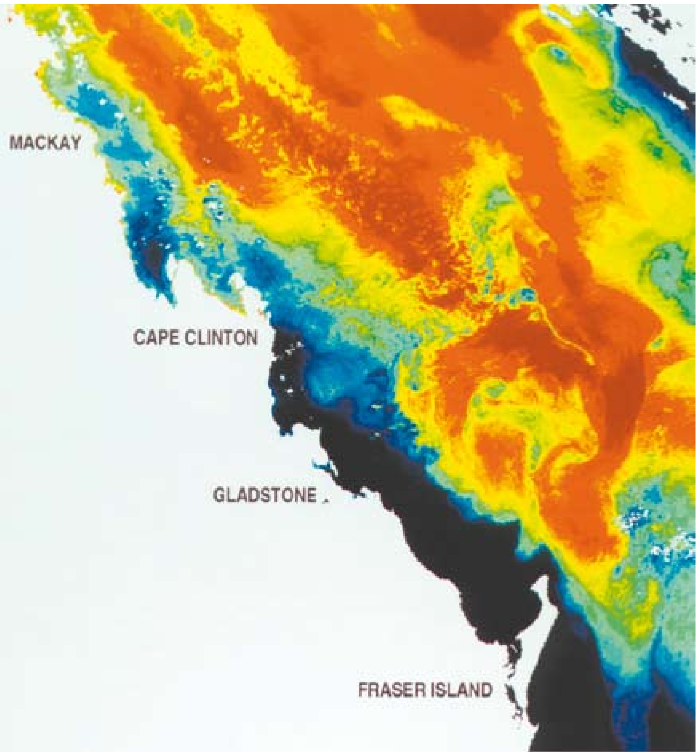
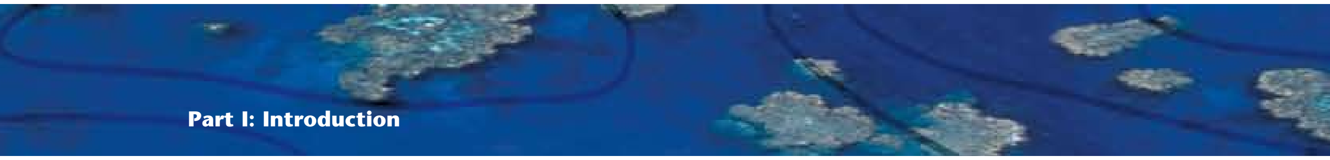


***Figure 3.13:*** *Sea surface temperature image of the southern GBR showing the EAC re-circulation off the Capricorn Bunker Group*



### 3.5.3 Wind generated currents

There are two main seasons in the sub tropical GBR and they are characterised by the south-east trade winds, that are prevalent from April to November encompassing the austral winter and the variable south-west monsoon, usually active from December to March during the summer. Low frequency winds are highly correlated spatially over the majority of the GBR[62], especially during the south-east trades which commonly reach 25 to 30 knots. The winds reinforce the northward flowing Hiri current and oppose the poleward flowing EAC causing a seasonal minimum in transport and occasional surface flow reversals. Closer to the coast the south-east trade winds dominate the inner shelf resulting in well mixed northward coastal currents[14]. Modelling studies by King and Wolanski[39] and Brinkman et al.[7] in the central GBR suggest there is a disconnect between well mixed, coastal wind forced currents moving north and mid-lagoon EAC driven currents moving toward the south. Overall, southeast trade winds force surface waters on-shore and will suppress upwelling along the coast and shelf edge. During the north-west monsoon, winds tend to be less consistent and lower in strength. Episodic coastal upwelling can occur to replace the surface waters transported offshore by the wind. Any change in the strength of the Asian Monsoon (see Lough chapter 2) will be a major determinant on the relative roles of the seasonal winds experienced in the GBR.



**Projected:**
Climate models predict stronger southeast winds are expected in the Coral Sea.

**Certainty:**
Medium – Modulations from the Asian monsoon and ENSO will dominate variability.

**Regional detail:**
Coastal boundary layer to extend seaward. The Hiri current will strengthen with the local south-east trades. The EAC will exhibit more pulsing due to these winds impeding the poleward flow.

### 3.5.4 Continental shelf waves

Continental shelf waves propagate freely into the GBR from distant meteorological forcing in the south[32,22]. They are subject to scattering into higher order modes as they reach Fraser Island and travel past the Capricorn Bunker group in the southern GBR[30]. Continental shelf waves are also generated locally along the GBR from atmospheric pressure and wind forcing. They produce relatively small currents of 10 to 20 cm per second, but can transport water large distances and are a major source of current variability on the continental shelf[63,44,9,14]. Shelf waves also displace the thermocline vertically along the shelf break and can lead to intermittent cold water intrusions as they propagate past reef passages[1].

**Projected:**
Changes to continental waves propagating from the south into the GBR will be due to any change in occurrence and intensity of weather systems in the south. The observed increase in the Southern Annular Mode affects those weather systems. How far these waves propagate into the central GBR remains unclear.

**Certainty:**
Low

**Regional detail:**
GBR generated waves are likely to increase in strength assuming local atmospheric perturbations in the wind and pressure fields increase.

### 3.5.5 Tide

Tides dominate the sea level variations of GBR waters and are a major source of energy for mixing in the GBR. They are a mixture of semi-diurnal and diurnal tides along most of the shelf with the exception of the region around Broad Sound in the southern GBR. Here there is a significant topographic amplification of the semi-diurnal constituents (Table 3.1).

The sea level height and the strength of currents along the GBR vary according to shelf width and the degree to which the reef presents a barrier to tidal flow. Tides are generally small in the deep ocean but are amplified over the wide and shallow continental shelves. For example, the tidal range at Elusive Reef on the seaward edge of the Swains reefs (offshore from Broad Sound) is only 1.7 metres.

***Table 3.1*** *Mean spring ranges (defined as mean high water springs minus mean low water springs) along the GBR from north to south*

| Location | Latitude | Range (m) |
|---|---|---|
| Harrington Reef | 11° S | 2.7 |
| Cairns | 16° S | 2.1 |
| Townsville | 19° S | 2.3 |
| Mackay | 22° S | 4.6 |
| Broad Sound | 22° S | 6.7 |
| Gladstone | 23° S | 3.9 |

The exceptionally large tides of Broad Sound in the southern GBR are due to the wide shelf (250 km) and the barrier effect of the offshore reef complex[45,6]. This barrier forces tidal flows to go around the reefs, both from the south, up Capricorn Channel and from the north, through the sparse reef matrix off Townsville in the central GBR, where they superimpose to form a macro-tidal standing wave.

A feature of the tidal current is that it tends to have a significant cross-shelf component near the shelf edge and is an important factor in regulating and mixing any slope water intrusions and upwelling processes[58,69,31]. The horizontal excursion of tidal waters at the shelf edge is limited to only a few kilometres however the tides play an important role mixing the cooler waters towards the surface. Satellite sea surface temperature imagery shows these thermal signatures (Figures 3.6 and 3.7).

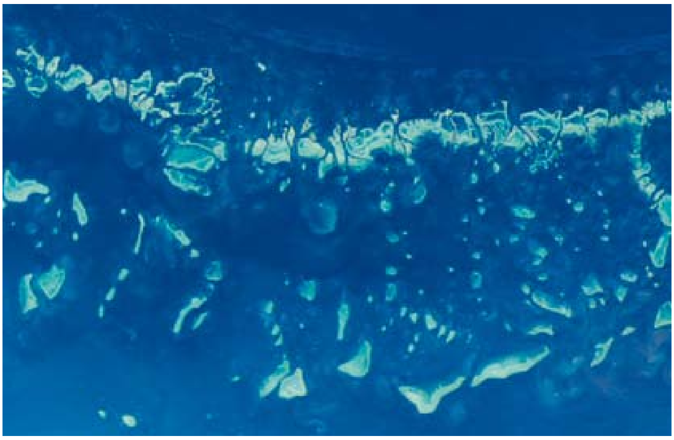
Tidal currents within the reef matrix also provide a source of enhanced mixing in the vicinity of the complex topography of the reefs. This causes flow acceleration and formation of tidal phase eddies in the lee of the reefs due to channelling of the flow (Figure 3.14). Eddies can then separate from the source reef and flow downstream influencing others in their path[62]. Predictable tidal currents are critical sources of mixing vertically around reefs especially during the summer monsoon season. Coral bleaching events are characterised by periods of high insolation and low wind speeds with alternative sources of surface mixing, to break down the stable surface layer, lacking.

**Projected:**
Gravitational tidal currents are not expected to increase significantly, however, as sea levels rise the tidal range will increase according to local shelf and coastal topography. Where waters can encroach on land, this effectively increases the shelf width, resulting in an amplification of the tidal range.

**Certainty:**
High

**Regional detail:**
Tides centred on Broad Sound in the southern GBR are likely to show the largest increase in tides along the GBR.

***Figure 3.14*** *Tidal phase eddies forming during a flooding tide after traversing narrow reef channels near Hydrographers Passage on the outer southern GBR*



## 3.5.6 River plumes

Consistent rainfall occurs in the wet tropics in the northern region where coastal mountain ranges provide the necessary uplift of the humid trade winds to produce rainfall, feeding the local rivers during the south-east trades. Two major catchments provide significant seasonal flows to the GBR during the monsoon and cyclone season (December to April) and are the main source of river plumes. The two major rivers are the Burdekin River in the central region and the Fitzroy River in the southern region. Freshwater plume dynamics control the direction of flow, with plumes turning northward at the river mouths (in the Southern Hemisphere) and following the coastline northward where the plumes are subject to mixing by wind and tide forcing[13]. Large flood events can bring flood waters to the outer reef in the narrow northern and far northern regions, and to a lesser extent in the central and southern regions where the shelf is wider[68,64,40]. Oceanic inflows through the Palm and Magnetic passages around 19° S inhibit cross-shelf surface flows of the plumes reaching the outer shelf reefs. A detailed review of riverine impacts on the GBR can be found in Furnas[26].

## 3.5.7 Upwelling

Throughout this chapter a recurring theme has been to identify processes that cause thermocline displacements along the GBR shelf edge. These displacements occur as a result of a large range of oceanographic processes: basin scale ENSO and PDO, EAC and Hiri current variability, impinging eddies and Rossby waves, tides, wind forced continental shelf waves and internal waves and tides on the thermocline itself[65,62].

Mechanisms that enhance the delivery of sub thermocline waters to the shelf include bottom generated Ekman layer currents[28], tidal induction[58], geostrophic pumping[47] and favourable winds and currents. The intruded waters may penetrate to the GBR lagoon but remain subsurface, such as found in the central GBR[3]. Waters however can mix upwards around the coral reef fringes within the reef matrix assisted by vertical mixing provided by the tides, wind and wave activity.

These processes affecting the depth of the thermocline are important to the health of the GBR as they control the relative amount of warm oligotrophic surface waters or cool nutrient rich waters that reach the continental shelf from the Coral Sea[4,41]. The intrusions from below the thermocline enhance primary productivity and alleviate heat stress experienced during coral bleaching events. Andrews[1] found that shelf break waters can be 1 to 4.5°C cooler than the surface lagoonal waters.

**Projected:**
Highly variable and episodic. Shallowing of the thermocline due to increased stability of the surface may allow the thermocline to lift above the shelf edge. Increased southeast trades will be less favourable. ENSO and PDO effects remain unobserved.

**Certainty:**
Low

**Regional detail:**
If the SEC bifurcation moves southward, the northward flowing Hiri current will deepen the thermocline resulting in the central and southern section reefs experiencing a reduction in nutrients and warmer waters. A waxing Hiri current and waning EAC result in a deepening thermocline along the entire GBR.

## 3.6 Conclusions

Climate change will affect GBR circulation patterns, the stability and depth of the surface mixed layer and the depth of the main thermocline. All these processes play an important part in regulating heat, connectivity, productivity and exchanges with the atmosphere. The heat content of the ocean is a fundamental environmental variable and influences the health of the GBR ecosystem. The Coral Sea also plays an important role in determining regional climate systems beyond the GBR. Northern Coral Sea waters through the Hiri current feed the WPWP and in turn the equatorial current systems that determine ENSO. The southern branch, EAC, sends warm tropical waters poleward affecting the climate along the eastern seaboard of Australia.

Given the sparse number of observations of the GBR and Coral Sea, it is therefore important to encourage initiatives such as CLIVAR's Southwest Pacific Circulation and Climate Experiment (SPICE) and dedicated regional array on the GBR that can monitor the EAC variability and structure over the longer term. The recent Australian Integrated Marine Observing System initiative goes some way toward achieving these goals for the GBR. Without these dedicated systems for long-term accurate measurements, detection of climate related change in oceanographic processes will remain unresolved or uncertain. Further modelling studies are needed to provide hypothesis testing on local affects of climate change through downscaling from global predictions.

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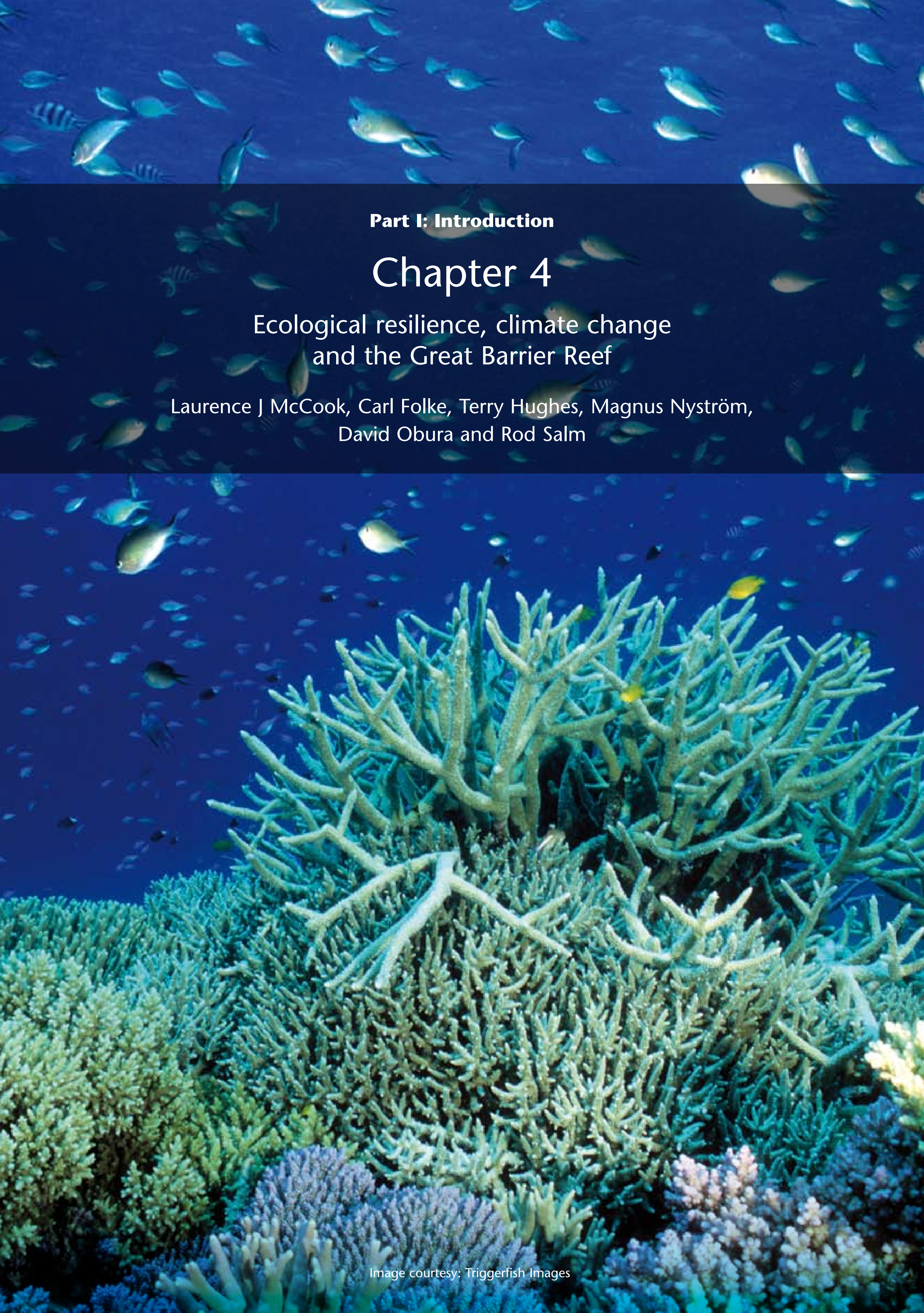
Part I: Introduction

# Chapter 4

## Ecological resilience, climate change and the Great Barrier Reef

Laurence J McCook, Carl Folke, Terry Hughes, Magnus Nyström, David Obura and Rod Salm



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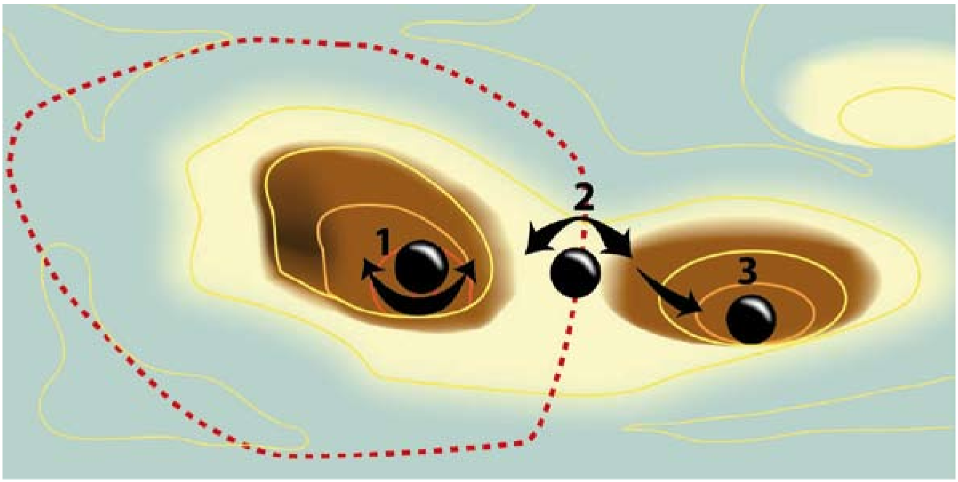
## 4.1 The concept of resilience in social-ecological systems

The vulnerability assessments in this volume frequently refer to the resilience of various ecosystem elements in the face of climate change. This chapter provides an introduction to the concept of ecological resilience, and its application as part of a management response to climate change threats. As defined in the glossary, *resilience refers to the capacity of a system to absorb shocks, resist dramatic changes in condition, and maintain or recover key functions and processes*, without undergoing "phase shifts" to a qualitatively different state (Figure 4.1)[32, 72]. For example, people who are physically and mentally fit and strong will have good prospect of recovery from disease, injury or trauma: they are resilient.

***Figure 4.1*** *Resilience, dynamic stability and alternate stable states (redrawn from Walker et al. 2004[73])*



In Figure 4.1, a ball placed at position 1 is dynamically stable: not only will it remain in position, but if pushed in any direction, it will return to its original position; thus the ball in this state is resilient, in that it can absorb shocks and return to a similar condition or state. In contrast, a ball placed at position 2 may be initially stable (it will remain in position if undisturbed) but not dynamically stable: if disturbed, it will move away. Thus the ball at position 2 is not resilient, and disturbances will result in a shift in state. If the ball at position 1 is disturbed to anywhere within the red circle, the ball will return to position 1; however, if disturbed further, the ball may not return, but may move to a new, alternate stable state (eg position 3). This system is resilient to disturbances that push it within the red boundary. However, if external factors decreased the depth of position 1, or lowered the saddle at point 2, then the system's resilience would be reduced. By analogy to coral reef ecosystems, position 1 might be a coral-dominated reef, and position 3 algal dominated. A disturbance such as killing coral that is overgrown by algae would move the reef toward an algal-dominated state; if the reef is resilient, this change would be temporary and natural processes would allow coral to re-establish and recover. If not, the algal dominance might be sufficient to preclude coral regrowth or recruitment, and the reef would change trajectory, moving toward algal dominance.

Ecological resilience refers to the capacity of an ecosystem, habitat, population or taxon to withstand, recover from or adapt to impacts and stressors, such as climate change, and retain the same structure, processes and functions[32]. For example, coral reefs are naturally very dynamic, undergoing constant change and disturbances, but, under natural conditions, they have considerable capacity to recover or maintain key processes and functions in the face of such disturbances or pressures. Tropical storms may cause dramatic damage to coral populations, and hence to the physical habitat structure, with dead coral being overgrown by various forms of algae. This will result in a temporarily changed state, and changes in ecological functions. On a resilient reef, over a period of five to 20 years, the altered state is unstable: coral fragments will regrow, and new corals will settle, grow and gradually replace the algae, restoring the reef to coral dominance, and restoring ecological structure and processes. In contrast, however, if human impacts have undermined that resilience, algal growth may be exacerbated, coral regrowth and colonisation may be suppressed, and the altered state and processes may become stable, causing a long-term "phase shift", or change, to algal dominance[33, 50, 37].

For ecosystems to persist in the long term, successful reorganisation (recovery) after disturbance is fundamental. However, coral reefs are facing pressures at local, regional and global scales that challenge their capacity to reorganise following disturbance and thus challenge their existence[31, 34,78]. Coral reefs exposed to gradual change are often assumed to respond gradually and smoothly. However, like most other ecosystems, they are dynamic, complex and adaptive[57]. Put simply, this means that they are characterised by environmental thresholds that, if crossed, may lead to large-scale and relatively abrupt shifts in state, including changes in ecosystem processes and structure (eg coral-dominated reefs shifting to algal dominance) and in their capacity for self-organisation[44, 24]. Ecological resilience also embraces adaptability, in the sense that an ecosystem may maintain characteristic structures and processes by developing new and innovative organisation or attributes. For example, in the Caribbean, sea urchin populations increased in response to overfishing of herbivorous fishes; in effect, the ecosystem reorganised to maintain the process of herbivory[30,33]. Importantly, once a threshold is crossed and a shift in state or key processes occurs, it may be difficult, or even impossible, to reverse the shift, due to changes in feedback mechanisms that stabilise the new state. Such reinforcing mechanisms may, for example, involve algae that prevent corals from establishing by occupying substratum, trapping sediments, releasing allelopathic chemicals, and overgrowing juvenile and low-relief adult coral colonies[51,7,67]. Reversing such a shift may require a different path, and restoring conditions to previous levels may not be sufficient (an effect known as "hysteresis")[35]. For example, the numbers and species of herbivorous fishes required to prevent algal overgrowth of corals may not be enough to remove an algal bloom once it has occurred. Reversal of such shifts may not only be difficult, but is likely to be significantly more expensive than prevention.

The concept of resilience provides a valuable integrating theme or perspective for both the science and management of natural environments, in particular because it addresses two of the most difficult challenges in understanding and managing human impacts on natural ecosystems: first, that different natural or anthropogenic (human-derived) stressors can interact, and synergise to cause more damage than either stressor alone[33, 52]; and second, that stressors and their impacts and interactions can be difficult or even impossible to predict. Individual human-derived stressors rarely occur in isolation: for example, for example, terrestrial runoff to reef waters, usually contains increased levels of several pollutants, such as sediments, nutrients and pesticides. Several studies have shown much higher impacts in response to combinations of pollutants than to individual pollutants[22]. If, as human populations grow, increased runoff co-occurs with overfishing, algal growth, enhanced by nutrients, may pass a threshold level, beyond which herbivorous fishes may fail to control algal abundance if their numbers have been reduced[50]. The result may be a sudden overgrowth of algae that is well beyond that accounted for by the nutrient runoff.

Interactions between chronic and acute disturbances are particularly significant. For example, on coral reefs, considerable evidence has emerged that while some chronic human-derived stressors, such as over-fishing or eutrophication (nutrient and sediment pollution), may have relatively small direct effects on established corals, they may severely limit the capacity of coral populations to recover after acute disturbances such as storm damage or mass bleaching due to sea warming. In this scenario, the chronic stressor may be of little immediate and direct threat to undisturbed reefs, but may reduce the resilience of the habitat, so that failure to recover from frequent, repeated disturbances may result in a gradual, piecemeal degradation or "ratchetting down" of reef health (Figure 4.2)[33, 52].

***Figure 4.2*** *Modelling the effects of chronic stressors, such as eutrophication, and repeated disturbance, such as mass bleaching, showing the potential importance of interactions (redrawn from McCook et al 2001[52]). Individual graphs represent the changes in coral (blue lines) and algae (brown lines) through time, for computer simulations of reef dynamics.*

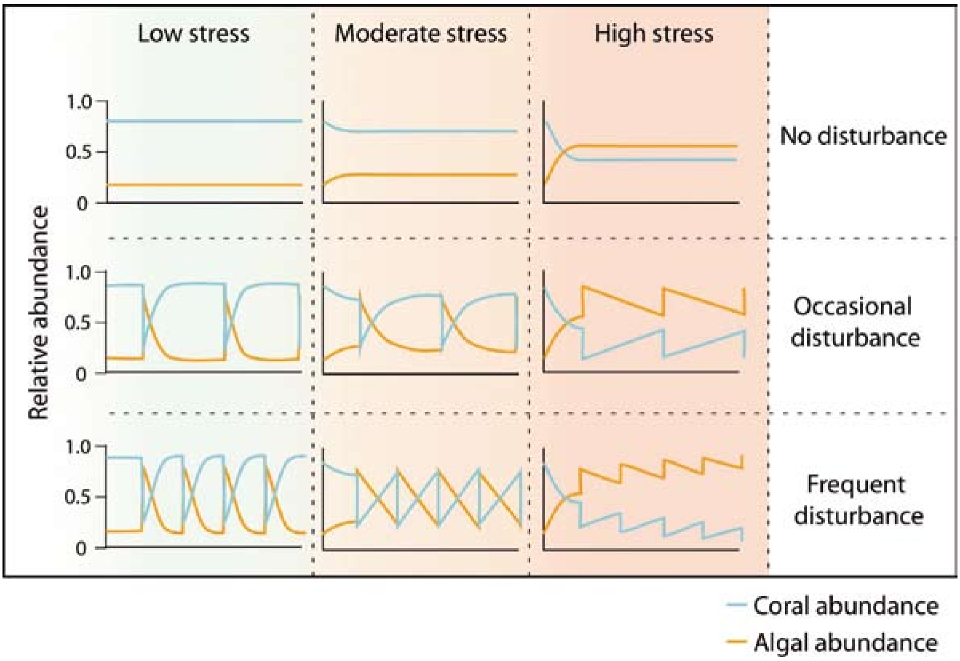


Figure 4.2 simulates the effects of increasingly frequent disturbances[52]. The graphs on the left show that the "virtual reef" is relatively resilient and coral populations recover after each disturbance, so that even with relatively frequent disturbances overall reef condition is maintained in the long term. The three graphs along the top row indicate potential effects of increasing stresses, such as overfishing or eutrophication. Reef condition declines with increased stress, but coral populations can persist at moderate levels: reef condition is moderate, but resilience is reduced by the stresses. However, when chronic stress is combined with frequent disturbance (bottom right graph), the reduced resilience means the reef cannot fully recover before the next disturbance, damage accumulates and there is a serious long-term decline in condition. Thus, this model reef community can persist with either frequent disturbances or chronic stresses, but becomes degraded if subjected to both impacts. This model illustrates two important points. Firstly, the chronic stresses do not appear to cause the coral declines in the bottom right panel; simple monitoring of this system would suggest the declines are caused by the disturbances. Only by understanding the processes that engender recovery and resilience do we recognise the critical role of the chronic stresses. Secondly, management strategies that seek to both reduce the frequency of disturbance (eg by mitigating climate change) and enhance the resilience (eg by reducing overfishing or runoff of pollutants) may be much more effective than either action alone.

The risk with this situation is that management actions that address stressors in isolation may fail if they do not address the potential interactions. In addition, they may fail to engender public support; for example, addressing pollutant runoff might be seen as wasted effort because the perception is that climate change will damage the reef anyway. By understanding these interactions, scientists, managers and the public will be able to see the value of specific management actions not only in addressing the specific risk, such as pollutant impacts, but also in maintaining the overall resilience of the ecosystem to resist or recover from other impacts.

The second benefit of managing for overall resilience, as well as for specific threats or impacts, is that it provides the best insurance against future unforeseen or unpredictable threats[42,26]. Several of the most significant threats to coral reefs in recent decades have emerged unexpectedly. The decline of Caribbean reefs was significantly increased by the completely unforeseen, wide-scale disease-induced mortality of herbivorous *Diadema* sea urchins in the 1980s. These herbivorous sea urchins had previously prevented algal exclusion of corals, and the impact of this die-off was much more severe because of the wide-spread depletion of herbivorous fish[33,8]. Similarly, the now wide recognition of the impact of climate change on coral reefs through increased mass bleaching was unforeseen 10 years ago[31]. It is likely that other currently unrecognised threats will emerge for reefs and other habitats within the Great Barrier Reef (GBR) until science identifies new threats, the best management strategy is to aim for a system with the resilience to recover from a wide range of possible challenges.

The concept of resilience is not limited to ecosystems in isolation from humans, but also applies to social and economic systems and it has been recognised for some time that social, economic and ecological resilience are strongly intertwined. Management actions aimed at protecting ecological resilience that also take account of the social and economic wellbeing of the community will generally be more sustainable and effective in the long-term. For example, marine protected areas that generate increased tourism revenue for local communities from the improved condition of ecological resources, or increase sustainability of fisheries, generate support in those communities, in turn generating improved compliance and enforcement[77,2]. Management that ignores or overruns the social or economic context will often be less effective, or fail, owing to a lack of local support or political intervention. Importantly, social, economic and ecological resilience are not inconsistent goals, and can be effectively integrated[27].

Resilience also provides a basis for integration of management strategies and responses to different issues, and for adaptive management approaches. Thus, management action to reduce terrestrial runoff may be markedly more or less effective, depending on the management of pressures on herbivorous fish populations[48,41]. It may be most beneficial to manage fishing pressure in areas with the highest runoff. Adaptive management requires that the effectiveness of current management practices be periodically reviewed as conditions and circumstances change, and as new threats emerge. The concept of resilience suggests that any review should include not only the apparent state of the ecosystem (or social-ecological system), but also the key processes and functions which confer resilience, and that management actions should respond or adapt to changes in those processes and functions[37].

## 4.2 Ecological resilience in the context of climate change

Human-induced climate change is a major threat to many ecosystems, including the GBR[31,34] (see chapters 5–22). In simple terms, two management approaches can be taken to minimise these impacts: reduce the extent of the changes; and maximise the capacity of the system to resist, adapt to, or recover from, those impacts (Figure 4.3). Overall, addressing the cause of the problem (for example, by abatement of greenhouse gas emissions) is critically important and likely to be the most effective approach. It is also likely to be the most cost-effective strategy overall, because it will ameliorate impacts on a vast range of systems, both human and natural. However, such measures are beyond the scope of marine management agencies, and will not be sufficient alone. Because there will be long lag times in the reversal of current climate trends (decades to centuries), ongoing change is inevitable for the next several decades (Lough chapter 2).

***Figure 4.3*** *Management responses to increasing pressure on coral reefs*

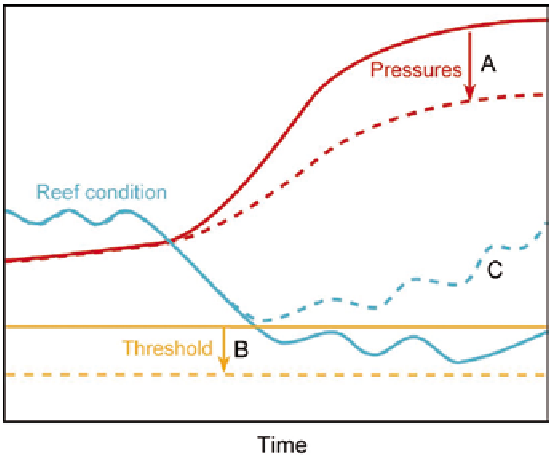


Figure 4.3 shows that the effect of pressures on reefs (solid red line) is predicted to increase dramatically over the next century, due to climate change and other human impacts. As a result, ecosystem condition is likely to decline, along with the capacity to recover from those impacts. If the loss of resilience is sufficient, reefs may pass a threshold beyond which they do not recover, but remain in an alternate, degraded state (solid green line). There are two complementary strategies available to managers. First, and paramount, is to reduce climate change and other human pressures on reefs (dashed red line); in the case of climate change, this requires action at global scales, and is beyond the scope of marine management agencies. Second is to manage other sources of stresses or pressures on the reefs, so that the decline in resilience is reduced and the ecosystem has enhanced capacity to maintain itself or to recover, rather than pass the threshold. Action on this strategy – managing for resilience – is challenging but possible for marine management agencies.

In this context, it is critical to maximise the capacity of the GBR ecosystem, and the communities and industries that depend on it, to adapt to climate change. However, as numerous chapters in the current volume illustrate, for many taxa and ecosystems there is a lack of detailed scientific understanding of the impacts, and an even greater ignorance of how to address those impacts directly. This makes it very difficult to develop specific management strategies for climate change adaptation. It thus becomes increasingly critical to maximise the resilience or capacity of the ecosystem to cope with changes generally. Management for resilience is therefore not only a general strategy for protection, but an important part of responding to the impending threat of climate change[34].

It is important to emphasise that abatement and adaptation are necessarily complementary strategies. Managing for resilience is unlikely to provide sufficient protection for the biodiversity of the GBR; rather, it aims to slow and reduce the impacts sufficiently to allow natural adaptation and abatement of climate change to occur. Good management of marine ecosystems must not be seen as reducing the need for strong and urgent attention on a global scale to a problem of global magnitude.

## 4.3 Aspects of the ecological resilience of the Great Barrier Reef

Of the numerous and varied habitats found in the GBR, the factors contributing to the resilience of coral reefs are best understood[57,46,34,5]. The following section provides a brief overview of some of these factors, although the discussion is intended to be illustrative, rather than exhaustive. Unfortunately, there is relatively little or no specific information available on the factors contributing to resilience of most other GBR habitats. This section therefore focuses primarily on coral reefs, as an example of the approach, and then only very briefly considers how the approach might apply to other habitats, and to species of particular conservation concern (such as dugong and other megafauna).

### 4.3.1 Factors contributing to ecological resilience of coral reefs

#### *4.3.1.1 Population condition and dynamics of reef-building corals*

The population condition and dynamics of corals, as the major contributors to reef construction, are fundamental to the capacity of reefs to absorb and recover from disturbances. Abundance of corals is an important factor, since disturbance to a reef with abundant coral will generally still leave some coral alive that can be a basis for population recovery. However, other key aspects include the diversity, fecundity, settlement and post-settlement survival rates and general metabolic and immunological condition of the corals[3]. It is important to recognise that a reef dominated by large but fragile corals may have a lower capacity to recover from a disturbance than a reef with less coral but more diversity of forms and higher recruitment rates. Similarly, low abundance of coral may simply reflect recent disturbance history, rather than overall low resilience. If coral recruitment and growth is high, reef condition may recover relatively quickly[47].

Coral population dynamics can have important indirect significance for resilience. For example, a reef with abundant and diverse corals is likely to have a complex, topographic structure that provides important habitat for other groups of organisms, thereby increasing biodiversity and potentially strengthening critical functions such as herbivory[71,50].

#### *4.3.1.2 Benthic algal assemblages and herbivory*

Competition between corals and benthic algae is fundamental to the abundance of corals on reefs. Algae may directly overgrow coral tissue, reduce the amount of light available for photosynthesis, abrade tissue, or produce chemicals that damage or kill coral tissue[51]. All of these effects will have significant metabolic costs to the coral, even if it is able to resist or defend itself.

Recent work has highlighted a particular, chemically mediated, mechanism of algal competition related to the microbial community on reefs. Plants release organic carbon into the water column and this has been found to increase microbial activity, which can result in coral tissue mortality[45,43,67]. Additionally, increasingly complex and long-living algal assemblages may accumulate larger microbial populations. Again, even if the coral tissue is not killed, these microbial stresses will have significant metabolic costs, reducing the capacity of corals to respond to other stresses.

Perhaps more significantly, algae may pre-empt space, inhibiting or preventing coral recruitment. Coral mortality is almost universally followed by colonisation by benthic algae of various forms (Figure 4.4)[15,17]. After wide-scale coral mortality, such as results from climate change-induced mass coral bleaching[31,78], the majority of substrate will be covered in various forms of algae, and recovery of coral populations will generally require recruitment on substrates dominated by algae (rather than on live coral, for example).[7] The nature of this algal assemblage will be fundamentally important to the success of subsequent coral settlement and growth. Substrate dominated by crustose coralline algae, with a sparse covering of short (less than 1 mm), fine filamentous turf algae, is likely to be highly favourable for coral settlement and growth. In contrast, a dense algal mat or thick growth of upright foliose or fleshy algae may severely inhibit coral settlement and survival, especially as such mats will often trap large amounts of sediment[7,37].

Under expected climate change scenarios, mass bleaching events are expected to occur with increasing frequency and severity[31]. Under these scenarios, algal overgrowth of dead corals and consequent algal dominance will become the norm, and coral populations are unlikely to recover sufficiently in between bleaching events. In such circumstances, the effects of different algal assemblages on coral recruitment, and on the recovery of surviving coral fragments, will become critical to the resilience of the reef, as will the effects of climate change on algal assemblages (Diaz-Pulido et al. chapter 7). It is likely that algal impacts on coral populations will become a real “bottleneck” for reef recovery.

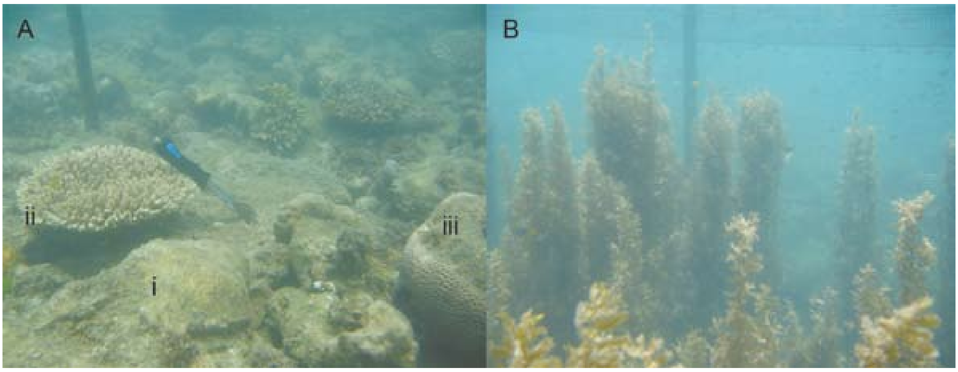
***Figure 4.4*** *Algal overgrowth of bleached corals in the Keppel Islands, Great Barrier Reef (August 2006). Severe bleaching of corals in the summer of 2006 resulted in extensive coral mortality and overgrowth by the alga Lobophora variegata. Previous work has shown* L. variegata *to be a highly effective competitor with corals*[40,41]*. The fate of these reefs will depend on factors such as herbivory, which influence the persistence of alga, and it's impact on coral regrowth and recruitment.*

Given the importance of benthic algae to coral populations, controls on the abundance and type of algae are critically important to reef condition. The primary controls on algal abundance and type on coral reefs are substrate availability and grazing by herbivores, usually fish or invertebrates such as sea urchins. The abundance and diversity of herbivores have been shown to be critical to long-term reef condition around the world. In the Caribbean, overfishing of herbivorous fishes resulted in a low-diversity herbivore community dominated by Diadema sea urchins. The sudden, regional scale die-off of sea urchins due to disease resulted in rapid increases in algal abundance, with subsequent declines in coral populations and failure to recover from disturbances[33,8]. Studies on the GBR have shown that herbivores are equally critical to algal distributions (Figure 4.5)[16,37,40,41,48,49,6]. Fortunately, pressure on herbivorous fishes is currently minimal, so this important element of reef resilience remains largely intact.

### *4.3.1.3 Biological diversity*

Marine ecosystems with high biological diversity will generally be relatively resilient, largely because they will have more diverse responses and capacities available to them, which can provide the basis for adaptation to new threats such as climate change[47]. This diversity may be at a range of levels, including genetic diversity within species, diversity of species within guilds (functional groups, such as corals or herbivores), trophic diversity, and complexity and diversity of habitats. For example, genetic diversity within a coral species, or diversity of the symbiotic zooxanthellae within a coral population, may provide greater capacity for the coral population to survive diverse stresses, and increase the likelihood of some individuals surviving a particular bleaching event[4]. Different species

***Figure 4.5*** *Effects of herbivory on resilience of a coral reef.[37] A. The reef crest at Orpheus Island, Great Barrier Reef, was severely damaged by mass bleaching in 1998,[37] resulting in overgrowth by fine, filamentous turf algae (i). Over the next few years, coral populations recovered by recruitment of new corals (ii) and by regrowth of surviving fragments (iii), with little impact from the filamentous turfs. B. In contrast, when large fishes were excluded to simulate the effects of overfishing, there was a dramatic overgrowth of* Sargassum *and other large, fleshy seaweeds, which reduced the growth and recruitment of corals and inhibited recovery of the community.*



and morphologies of coral have different susceptibilities to temperature-induced bleaching and to other threats; a reef dominated by a few coral types may be more vulnerable to widespread damage than a more diverse reef[46]. A reef with a diverse range of herbivores will have greater capacity to remove or prevent outbreaks of different types of algae[6], and will be less vulnerable to events such as the disease outbreak that killed *Diadema* sea urchins in the Caribbean. Diversity of habitats within an ecosystem increases the likelihood of some habitats being less severely impacted by particular stresses or disturbances[47]. For example, shallow reefs are often more vulnerable to storm damage and to coral bleaching. Deeper reef areas or areas with more complex topography may provide refuges that can be a source population for repopulating damaged areas.

Diversity within guilds has two aspects that underpin resilience: *redundancy* and *response diversity. Redundancy*[74,70,6] describes the capacity of one species to functionally compensate for the loss of another within a functional group. Some species that seem unimportant may become critical for reorganisation when conditions change, whether slowly (eg increasing seawater temperature, accumulation of nutrients) or abruptly (eg crown-of-thorns or disease out-breaks, hurricanes, bleaching events). Thus, in the Caribbean herbivore example, the presence of sea urchins suppressed algal overgrowth, even when herbivorous fishes were overexploited. The critical importance of herbivorous fishes only became apparent when disease wiped out the sea urchins[33, 8]. However, if all species are affected by a disturbance in the same way, even having a large number of species in a functional group may not contribute to resilience. *Response diversity*[20] describes the variability of responses within functional groups to disturbance[10]. A wide range of responses enables some species to compensate for others, which facilitates regeneration after a disturbance. Although it is not clear to what extent aspects of biodiversity contribute to resilience, it is clear that different aspects will be important under different circumstances.

### 4.3.1.4 Connectivity

The capacity of reefs to recover after disturbances, or reorganise in the face of new stresses, depends critically on the supply of larvae or propagules available to reseed populations of key organisms, such as fish and corals[38,63]. Most marine organisms have a planktonic larval phase, in which larvae are dispersed by a combination of active behaviour, such as swimming, and passive transport by ocean currents. Connectivity refers to the extent of the connections between reefs and source populations, which may be other reefs or other habitats, such as coastal mangroves (for many fish), inter-reef seafloor, or seagrass beds[19,55]. Patterns of connectivity depend strongly on ocean currents, the length of time that larvae remain viable in the plankton, and the existence of upstream habitats with refuge source populations. Even if a reef is well protected and soundly managed, alterations in the surrounding seascape may erode resilience if the supply of critical processes and functions, such as coral recruitment, is cut off[47].

Over short spatial and temporal scales, connectivity provides for the dispersal of both larvae, enabling recolonisation of sites, and adult organisms, potentially supporting ecological functions such as herbivory. Recent studies indicate that reef populations are overwhelmingly self-seeding[69,13], due to a combination of hydrographic and biological properties that retain larvae and/or strongly dilute a larval pool as it disperses from its source. When disturbances or stresses reduce the capacity for self-seeding, connectivity plays a critical role.

At larger spatial and longer temporal scales, connectivity provides the means of exchange of genetic material, and thus the currency of diversity, in space and time. Over multiple generations, connectivity maintains genetic continuity within populations and species, and defines the biogeographic spread of species. Resilience operates at many scales, and connectivity provides a mechanism for spreading and sharing resilience properties among locations. Thus ‘connected’ locations influence one another to varying extents in terms of resilience. Different ecosystem properties may operate across different scales, and degradation in multiple parts of a seascape may be masked by overall connectivity and sharing of resilience. Fragmentation of a seascape by the erosion of resilience in different locations may make the overall ecosystem vulnerable. For example, if the connectivity of a critical process is undermined by a disturbance event, the ecosystem may be pushed beyond a previously hidden threshold.[57]

Connectivity may also reduce resilience, if it facilitates dispersal of undesirable factors, such as disturbance, pollutants (eg nutrients) or organisms (eg diseases, algae, exotic species). The success of undesirable, invasive species will depend on the resilience of individual reefs within the seascape mosaic. Erosion of resilience at local scales may create dispersal refuges for undesirable organisms.

### 4.3.1.5 Refugia

Refugia are areas where ecosystems are unaffected by, or protected from, stressors or disturbances that reduce resilience. Refugia help to maintain diversity and abundance by serving as sources for replenishing the disturbed populations that underpin connectivity, and serve as stepping stones for maintaining connectivity across larger scales. Important features of refugia include sufficient location and separation distances to ensure connectivity, adequate extent to provide sufficient source populations, and inclusion of comprehensive and representative examples of the different habitats within a region[34,36,54].

A primary tool in marine protected area management is establishing no-take zones that aim to provide refuges from human stressors. They thus maintain the resilience of local sites, and of the overall system, through connectivity with each other and with adjacent zones open to human uses[54,36]. While it is clear that a higher proportion of a seascape maintained within refugia will provide greater protection on the whole, the nature of the relationship is as yet only approximately estimated. However, the irreversibility and threshold behaviour discussed above suggest that insufficient refugia will likely have serious long-term consequences[5].

#### *4.3.1.6 Water pollution and environmental quality*

The quality of the chemical and physical environment is a strong determinant of resilience. A poor-quality environment exacts significant costs to organisms in maintaining physiological health and integrity and in maintaining ecosystem function. In particular, good water quality is critical to the health of corals, and to ecological processes such as the recruitment of corals and coral-algal competition, both of which are important for ecosystem resilience[68,50,29]. In most nearshore tropical marine ecosystems, poor water quality is manifested as a long-term chronic increase in anthropogenic inputs of nutrients, sediments and other pollutants[39]. Recent work has particularly emphasised the role of excess organic carbon in reducing the resilience of coral populations[43,45].

A considerable body of recent research suggests that a major impact of poor water quality is not in direct effects on corals or coral-algal competition, but in the inhibition of recovery from other stresses and disturbances[50,79]. For example, after mass bleaching events, excess sediments and nutrients may inhibit coral recruitment synergistically with increased algal growth, with the result that coral populations re-establish too slowly to recover between disturbances[21]. Suppressed physiological health may also increase susceptibility to thermal stress and coral bleaching, given the metabolic costs of bleaching (the loss of the photosynthetic zooxanthellae). Modelling work has shown that a ecosystem able to cope with either frequent disturbances or eutrophication may show serious long-term degradation if the two occur in combination, amounting to a critical loss of resilience (Figure 4.2)[52].

From a management perspective, however, improving environmental quality provides one of the most accessible tools for maximising resilience to many other threats, from chronic fishing pressure to acute disturbances. In the classic case study of Kaneohe Bay in Hawaii, reductions in pollution delivered to the relatively enclosed bay were followed by partial recovery of reefs from a degraded, eutrophic state to a healthier condition[68]. On the GBR, water quality is being addressed proactively through the Reef Water Quality Protection Plan (see Section 4.6).

#### *4.3.1.7 Aspects of resilience specific to climate change*

As well as the general resilience factors discussed above, there are a number of environmental, ecological and physiological factors that relate directly to climate change-specific threats[75,59]. Most work to date has focused on thermal stress due to climate change; other impacts, especially acidification, are likely to be important (Fabricius et al. Chapter 17). The factors listed below have been shown to reduce thermal stress, coral bleaching or mortality in some cases. However, it is important to recognise that these factors are not always sufficient, and that they do not act independently. Addressing one in isolation of others, and of other processes that affect coral health and resilience, is likely to be ineffective.

### Thermal protection

Some reef areas appear to avoid or be protected from the oceanographic conditions that induce coral bleaching. This may be due to reduced water temperature, reduced light levels, and/or increased flushing. At large scales, these conditions may be induced by oceanographic and climatic features such as upwelling zones, current systems or regional climates that increase cloud cover, storms or cyclones[66]. At local scales, some corals and habitats appear to be protected from the worst thermal conditions by local topographic features that provide shading, screening or other micro-environmental variation[3].

### Thermal resistance

Some reef areas, zones, patches and individual corals appear to be resistant to thermal stress and show less bleaching and/or mortality than other areas or corals under similar conditions. Resistance may be related to intrinsic (genetic) or extrinsic (environmental) factors. Genetic factors include the identity of the coral species and of the symbiotic zooxanthellae, and individual variation. In particular, some clades (genetic groups) of zooxanthellae have been found to be more resistant to bleaching than others[4]. Environmental factors include conditions that allow corals to acclimate to higher temperatures or to variability in temperatures[53,18].

### Bleaching tolerance

Some reef areas, zones, patches or individual corals appear to be more tolerant to bleaching and suffer less mortality after bleaching than other areas or corals. Tolerance may also be related to intrinsic or extrinsic factors, but appears to be distinct from resistance to thermal stress[65].

These factors may be useful to reef managers in identifying and protecting areas of potential resistance and resilience of coral reefs to climate change. For example, areas that appear to have survived or recovered rapidly from previous bleaching might, in principle, be suitable sites for protection. However, to date no two mass bleaching and mortality episodes at a site have followed very similar patterns, so caution is needed and a range of resilience factors must be considered simultaneously, including the predictability and regularity of their occurrence[75].

### *4.3.1.8 Minimising bleaching impacts at local scales*

There can be no doubt that the most effective strategy to reduce bleaching impacts on coral reefs is to minimise climate change drivers. However, given that significant change is now unavoidable, it is also necessary to take every possible step to minimise the impacts of that change at local scales by addressing the various factors outlined above. It is likely that the two strategies, proceeding in tandem, may have synergistic benefits for reefs. Thus, in general terms Salm et al.[64] recommend that managers (a) identify and protect from direct anthropogenic impacts, specific patches of reef where local conditions are highly favourable for survival generally, and that also may be at reduced risk of temperature-related bleaching and mortality and (b) locate such protected sites in places that maximise their potential contribution to the recovery of damaged or vulnerable reefs that are connected through larval dispersal.

**Table 4.1** *Summary of local management approaches for mitigating climate change impacts on coral reefs*

| R2—Reef Resilience Toolkit[56] | A Global Protocol for Assessment and Monitoring of Coral Bleaching[61], A Reef Manager's Guide to Coral Bleaching[53] and other approaches[9,60] |
|---|---|
| 1. Managing for risk: representation and replication—protecting multiple examples of a full range of reef types helps to ensure inclusion of representatives of the area's total reef biodiversity. Replication of each reef type reduces the chance of any one type being completely compromised by an unmanageable impact such as a major bleaching event.<br>2. Refugia—Identifying and fully protecting coral communities that demonstrate bleaching resistance and that can thus serve as refugia is an effective way to facilitate reseeding and recovery of other areas that are seriously damaged by bleaching.<br>3. Connectivity—Identifying patterns of connectivity among source and sink reefs, so that these can be used to inform reef selection in the design of marine protected area networks and provide stepping stones for larval dispersal over longer time frames, is an important step in building resilience into networks.<br>4. Effective management—Managing reefs for both health and resilience and monitoring multiple indicators of the effectiveness of current actions are the bases for adaptive management. Effective management is fundamental to the success of any conservation effort and the daily business of managers' work. | 1. Use the ability to predict bleaching events to enhance coral reef monitoring programs; try to obtain pre- and post-bleaching data.<br>2. Establish monitoring protocols to answer specific questions about the causes and effects of bleaching events.<br>3. Use remote sensing tools to increase the level of predictability.<br>4. Use the ability to predict bleaching events to gain the attention of the public and to solicit their assistance in coral reef conservation.<br>5. Use the severe impacts of coral bleaching as a way to leverage other conservation measures such as reducing point and non-point sources of pollution.<br>6. Use coral bleaching events as a way to increase the public's awareness and peer pressure as to the need to cease destructive fishing practices.<br>7. Contact coral reef users and encourage them to lessen their direct impact on coral reefs during these stressful periods.<br>8. Engage divers in providing education and outreach messages about coral reefs so they can take direct action to lessen their physical impacts on the corals during stressful periods.<br>9. Communicate the long-term impacts of coral bleaching to reef users and solicit help in communicating to decision-makers the kinds of appropriate actions that need to be taken regarding climate change.<br>10. Identify coral reefs that are resistant to bleaching and develop criteria that will aid in the design of marine protected areas.<br>11. Establish fully protected reserves in areas resistant to coral bleaching.<br>12. Enlist the scientific community to assist in communicating the long-term trends that can be expected if current trends of climate change continue.<br>13. Integrate the geological and biological sciences in such a way as to hindcast our observations into geological times in order to forecast the long-term expectations for coral reefs. |

More specifically with respect to mitigating climate change impacts, The Nature Conservancy's R2 toolkit: building resilience into coral reef conservation[56] recommends a four-level approach (see Table 4.1) that condenses practical application of lessons learned by marine protected area managers during past bleaching events, such as those developed in the Florida Keys National Marine Sanctuary[9,60] and the GBR[61,53]. The development of management approaches that emphasise resilience and its application to mitigating the effects of climate change has accelerated with the recognition of the potential for a resilience approach. Management approaches have advanced from making general recommendations[76,64] to providing increasingly technical and specific ones[28, 53], and are turning towards specific recommendations for monitoring and assessment protocols for protected areas that focus on climate-related and resilience indicators[61].

### *4.3.1.9 Social and economic resilience and governance effects on ecological resilience*

There are key points at which the ecological resilience of coral reef can be influenced by socio-economic and governance factors (and vice versa)[24,2,1,12]. This discussion does not aim to fully explore these aspects, or to discuss social, economic or governance issues generally (Fenton et al. chapter 23), but rather to illustrate their relevance to ecological significance. Social and economic conditions influence patterns of reef use and impacts, such as fishing practices and terrestrial land management[2,1]. Fishing practices may be carefully managed, as on the GBR, or may include destructive fishing techniques such as the use of explosives, nets or cyanide. This will have major consequences for the abundance, diversity and connectivity of key fish populations, as well as corals (through direct damage from explosives, etc). Similarly, social and economic contexts are critical to the nature of land management practices, such as land clearing and intensive use of chemical fertilisers and pesticides in farming, and to the capacity of local communities to modify those practices to reduce impacts on reefs or other habitats. Indeed, social and economic factors are the basis of threats to ecosystem resilience, and effective management of those threats requires strategies that are socially and economically sustainable[14,25,58].

In this context, the significance of governance arrangements is receiving increasing recognition. Governance relates to the community's capacity to make choices that impact on environmental quality, biodiversity conservation and the like, and the efficacy of implementing those choices. Although governance includes political will and the role of governments, it also includes broader aspects, such as the engagement of various community sectors with reefs and their management. Again, because all local threats to resilience relate to the activities of people, governance and its efficacy directly influence whether resilience is undermined, preserved or strengthened[12, 62, 27].

## 4.4 Resilience of non-reef tropical habitats, ecosystems and processes

Although most scientific attention focuses on the coral reefs of the GBR, an estimated 94 percent of the area of the Marine Park consists of habitats other than coral reefs. This area includes deep seabed, shoals, sponge gardens, sand and mud bottom, deep water seagrass beds, beds and mounds of the calcifying green seaweed *Halimeda*, continental shelf slopes and intertidal mudflats and seagrass beds. Not surprisingly, little is known about the factors that contribute to the resilience of most of these habitats; subsequent chapters in this volume assess the vulnerability of these habitats to climate change (Diaz-Pulido et al. chapter 7, Waycott et al. chapter 8, Kingsford and Welch chapter 18). However, the general principles of maintaining physical, ecological and chemical processes and structures provide a strong starting point. The major pressures on these habitats are likely to include trawling and line-fishing for top predator fishes, and effects of terrestrial runoff, principally in inshore areas[11]. Trawling can dramatically disrupt the physical structure of sea bottom habitats, such as sponge gardens and seagrass beds, and also alter ecological structure by removal of target and bycatch species. The major impact of line-fishing is on food-web structure through the removal of top predators, many of which are highly mobile and provide a basis for connectivity between habitat areas and types. Terrestrial runoff contains increased loads of sediments, nutrients and pesticide pollutants (including herbicides), which can interfere with the ecological functions of inshore habitats such as seagrass beds[39,11].

In the absence of better information, potential management responses to these pressures can initially only focus on ensuring that sufficient proportions of the ecosystem are protected from the known and likely pressures. These responses include establishing comprehensive, adequate, representative and replicated refuges in spatial arrangements that provide a basis for connectivity, and seeking to reduce excess runoff of sediments, nutrients and pesticides. Reduction of herbicide pollution is particularly important for preserving the resilience of the extensive inshore intertidal seagrass beds[11]. Similarly, mangrove forests face potetntial negative impacts from a range of climate related factors, with a range of management measures to mitigate these climate related impacts possible.

## 4.5 Resilience in the context of species conservation

Many species of particular conservation interest, such as dugongs, turtles, sharks, dolphins and whales, are highly vulnerable to human impacts. This is often due to the nature of their life cycles; they may have low rates of reproduction, even under ideal conditions, or 'bottlenecks' that are particularly vulnerable to disruption, such as turtle nesting sites. Although populations of these species may be resilient when abundant, many are already strongly depressed due to intensive hunting or fishing, or other causes. Under such circumstances, even with strong protection, rates of population recovery are unavoidably slow, and show little capacity for improving resilience. This suggests that reducing or even completely removing pressures and stresses on these species, and managing for resilience, is not likely to be sufficient to regenerate populations within a few decades. This is a particular concern in the context of climate change, which is likely to exert significant additional pressures (Chin and Kyne chapter 13, Hamann et al. chapter 15, Lawler et al. chapter 16) that populations will have little capacity to absorb, adapt to, or recover from.

## 4.6 Management approaches to maintain resilience of the Great Barrier Reef

On the GBR, management approaches have focused on critical issues considered to be threats to the ecosystem, such as water quality, sustainability of fishing, and tourism activities[a]. However, it is important to recognise that these management issues are not independent. For example, on coral reefs, it is known that herbivorous fish can graze down enhanced growth of algae due to nutrient increases, providing protection against algal exclusion of corals[41]. Protecting fish populations thus provides additional protection against terrestrial runoff of nutrients. Similarly, minimising pollution of reef waters may maintain habitat for herbivorous fishes[50].

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[a] http://www.gbrmpa.gov.au/corp_site/info_services/publications/brochures/index.html

The Great Barrier Reef Marine Park is jointly managed by the Australian Government and the Queensland Government. The Great Barrier Reef Marine Park Authority focuses on protection of the ecosystems and maintenance of the World Heritage values of the Marine Park, and the Queensland State Government is responsible for day-to-day management, fisheries management and most catchment management activities.

The Great Barrier Reef Marine Park Authority and the Queensland State Government have jointly implemented the Reef Water Quality Protection Plan[b], aimed at directly addressing terrestrial runoff into the GBR. The Great Barrier Reef Marine Park Authority has also implemented a new Zoning Plan, which increases protection of biodiversity[c]. Because this Zoning Plan provides increased protection for fishes, it will also provide indirect support for the aims of the Reef Water Quality Protection Plan. The integration of these and other measures will enhance the overall resilience of the ecosystem to deal with a range of threats, not limited to the original issues, and in turn protect the sustainability of reef-dependent industries and communities. Importantly, these threats include the impending impacts of climate change (see subsequent chapters).

### The Great Barrier Reef Marine Park Zoning Plan 2004

Aims to provide comprehensive, adequate, representative and replicated protection of biodiversity in no-take areas, with 33 percent of the total area of the Marine Park in highly protected areas, and more significantly, a minimum of 20 percent of each of the 70 bioregions[23d]. The main activities that are regulated by the Zoning Plan include fishing, collecting, research, tourism, boating and shipping. Allocating a relatively high proportion of refuge areas aims to maintain natural biodiversity, and, through careful design of the Zoning Plan, ensure connectivity between relevant areas (eg fish spawning areas and habitats).

### Reef Water Quality Protection Plan

A joint initiative by the Australian and Queensland Governments, the Reef Water Quality Protection Plan aims to halt and reverse the decline in the quality of water entering the reef within ten years. This initiative addresses a major component of ecosystem resilience, and importantly, requires most changes to take place in the catchment upstream of the GBR. The GBR catchment lies outside the jurisdiction of the Great Barrier Reef Marine Park Authority, and therefore implementation is largely the responsibility of communities, rural industries and local governments.

### Tourism and recreational use

Tourism and recreation are carefully managed and monitored by the Great Barrier Reef Marine Park Authority through the Zoning Plan, Plans of Management in high use areas such as Cairns and the Whitsunday Islands, limits on use (aimed at addressing carrying capacities), permits and environmental impact assessment requirements for significant developments.

### Fishery Management Plans

Primarily the responsibility of the Queensland State Government, these include Plans for Fin Fish and Coral Reef Fisheries, with an Inshore Fisheries Management Plan currently in development. These plans focus on fisheries, rather than ecosystem health, and the Great Barrier Reef Marine Park Authority works closely with the State Government to ensure the plans are consistent with the need to protect the values of the GBR.

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[b] http://www.gbrmpa.gov.au/corp_site/key_issues/water_quality/rwqpp.pdf

[c] http://www.gbrmpa.gov.au/corp_site/management/zoning

[d] http://www.gbrmpa.gov.au/corp_site/management/zoning/rap/rap/pdf/rap_overview_brochure.pdf

Importantly, these various management initiatives are not implemented in isolation, but rather as an integrated, ecosystem-based package of complementary measures. They seek to address the *cumulative* impacts and interactions between impacts, and not just individual issues. As outlined above, there are potentially powerful synergies in, for example, simultaneously minimising inputs of sediments, nutrients and pesticides, and ensuring fish biodiversity and abundance is sufficient to maintain processes such as herbivory. Inshore areas are especially vulnerable to over-use, and to impacts of water quality, and so are carefully considered in both Plans of Management and Fisheries Management Plans. Importantly, the broader community increasingly recognise the value of this complementary and integrative approach over single-issue initiatives. In combination, these measures enhance the resilience of the ecosystem to other stresses and enhance the links to social systems. Thus, where previously managers were criticised for addressing water quality while climate change was of even greater concern, it is increasingly understood that the best protection against current and emerging threats, including climate change, is to ensure the ecosystem is as resilient as possible.

Also significant is the incorporation of adaptive management approaches into the management of the GBR. Thus, both the Reef Water Quality Protection Plan and the new Zoning Plan were developed in response to emerging scientific evidence that existing management activities were insufficient to ensure the long-term resilience of the ecosystem. Emerging understanding of the biodiversity of the GBR showed that previous zoning did not provide sufficient coverage of many bioregions. New research and monitoring suggested that degradation of inshore habitats was the most likely outcome of previous land-use practices[39]. Management is continuing this adaptive approach, developing monitoring and research programs to assess the adequacy and impacts of management actions and strategies, as a basis for future policy development, refinement and adaptation. Included are programs that focus on specific management initiatives, such as the Zoning Plan and the Reef Water Quality Protection Plan, and programs that assess the overall status of the ecosystem, and the related industries and communities.

## 4.7 Outlook: resilience in the face of changing climate

A key aspect of an adaptive management approach is the realisation of the emerging but urgent need to prepare for the effects of global climate change on the GBR and its habitats. Effective measures to achieve this will require the best possible information about the likely vulnerability to climate change of the various ecosystems and taxa. The present volume is intended to make a start in compiling that information, and clearly demonstrates that impacts are likely to be not only dramatic, but also very difficult to predict with any precision. There is, and is likely to remain, considerable uncertainty about the nature and extent of direct effects and of their interactions with other stressors. As an emerging area of science, assessment of vulnerability to climate change tends to focus on direct effects of climate change on systems and processes, perhaps considering interactions between impacts or stressors (eg climate change and overfishing or eutrophication). However, climate change stressors will also affect the ability of these systems and processes to respond to other stressors. This means that the resilience of the various ecosystems and taxa is likely to be threatened to an unprecedented extent. This, along with the considerable inherent uncertainty about these changes, will significantly increase the challenge of adaptively managing and maintaining ecosystem integrity. Chapter 24 of this volume (Marshall and Johnson) aims to take up this challenge.

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**Part II: Species and species groups**

# Chapter 5

## Vulnerability of marine microbes on the Great Barrier Reef to climate change

Nicole Webster and Russell Hill

> *I make no apologies for putting microorganisms on a pedestal above all other living things. For if the last blue whale choked to death on the last panda, it would be disastrous but not the end of the world. But if we accidentally poisoned the last two species of ammonia-oxidisers, that would be another matter. It could be happening now and we wouldn't even know...*
>
> Tom Curtis (July 2006) in Nature Reviews Microbiology

Image courtesy of Dennis Kunkel Microscopy Inc.

## 5.1 Introduction

Global climate change will have a direct effect on the Great Barrier Reef (GBR) as discussed in previous and subsequent chapters. The primary effect of climate change will be a 1 to 3°C increase in global sea surface temperature along with sea level rises as predicted by Intergovernmental Panel on Climate Change (IPCC) models. Other associated effects include increased acidity and increased terrestrial inputs. The effects of climate change will have a significant impact on marine microbes, potentially altering microbial diversity, function and community dynamics. Although microbes constitute by far the largest diversity and biomass of all marine organisms, they are often ignored in discussions about the impacts of climate change (Figure 5.1). This is despite the fact that the vast microbial life on our planet plays a central role in either accentuating or mitigating the effects of climate change. Since microbes are central to the global cycles (including carbon, nitrogen and trace gases), changes to temperature, nutrient availability and environmental pH will have major impacts on microbial processes central to the climate debate. This chapter will discuss the exposure, sensitivity and impacts of climate change on marine microbes at global, regional and local scales, providing examples of observed impacts in marine ecosystems. In doing so, the adaptive capacity and vulnerability of marine microbes to climate change will be assessed. The background provided in this chapter emphasises the importance of marine microbes and outlines why they require greater appreciation in research effort and consideration in predictive climate models.

### 5.1.1 Tropical marine microbes

With more than a billion micro-organisms in a litre of sea water, the biodiversity of microbial communities (Figure 5.1) and the functional roles they play in the marine environment (Figures 5.2 and 5.3) are hugely significant. Limitations with traditional culture-based methodologies (generally only 0.1% to 1% of marine microbes can be recovered on culture media by conventional approaches) mean that the diversity, phylogeny and function of marine microbes have remained largely unexplored. However, with the advent of molecular techniques, we are now discovering a huge diversity of marine micro-organisms[90] and uncovering a wide range of previously unknown microbial functions[35,52,43]. The functions and species composition of bacterial communities across the globe, including those of the GBR, may be adversely or positively affected by climate change. Shifts in microbial community structure may subsequently enhance or mitigate the effects of further climate change.

Marine microbes are highly abundant, with global oceanic densities estimated at $3.6 \times 10^{29}$ bacterial cells[90], $1.3 \times 10^{28}$ archaeal cells[58] and $4 \times 10^{30}$ viruses[92]. Currently, estimates of marine bacterial diversity range from only a few thousand species[42] to as many as two million distinct taxa[19]. Most analyses use a criterion of more than 97 percent sequence identity in the small subunit of ribosomal RNA to define a species or taxon. However, Fuhrman[33] points out that physiological and genomic differences may indicate a division on an even finer scale, suggesting that previous estimates of marine bacterial diversity may be too low[33]. Additionally, recent research by Sogin et al.[90] examined microbial diversity in the North Atlantic and discovered that, while a relatively small number of microbes dominate, thousands of low-abundance microbes actually account for the majority of phylogenetic diversity. Sogin et al.[90] concluded that ‘this rare biosphere is very ancient and may represent a nearly inexhaustible source of genomic innovation’.

**Figure 5.1** *Estimated number of marine species*

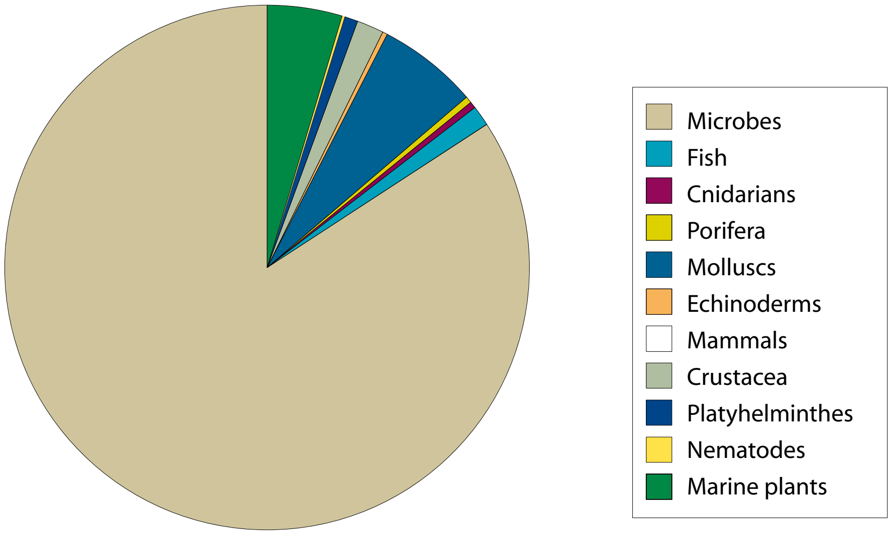


**Figure 5.2** *Ecological roles of marine microbes on the Great Barrier Reef*

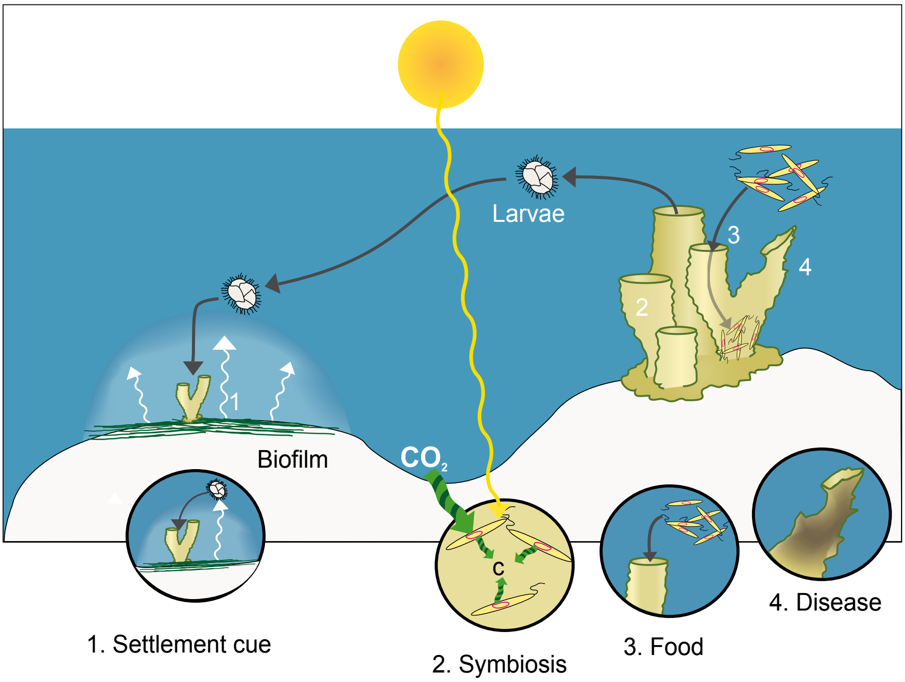
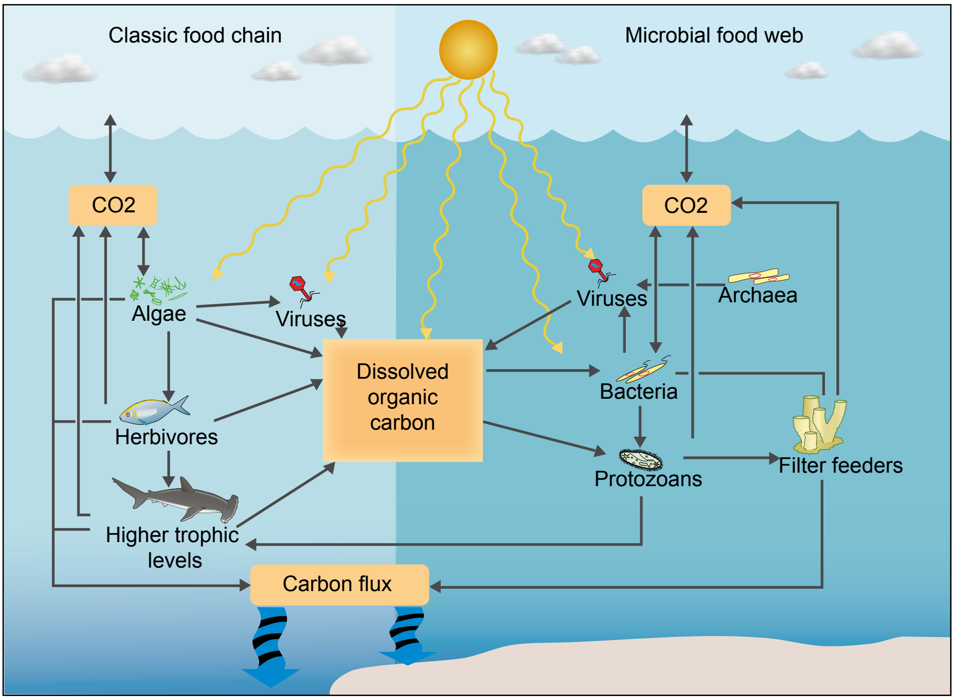


***Figure 5.3*** *An overview of the classical food chain and microbial loop (Adapted from DeLong and Karl[24])*



## 5.1.2 The functional role of marine microbes

### *5.1.2.1 Nutrient cycling*

Changes in rates of bacterial photosynthesis or inorganic flux through the microbial loop can have major impacts on carbon cycling and on global climate. Bacteria are estimated to be responsible for 20 to 50 percent of marine primary productivity[16,29] and perform fundamental roles in the degradation of organic matter. In the upper 500 metres of the ocean, microbes consume an estimated 75 percent of the sinking particulate organic carbon flux[16]. Marine microbes are also crucial to various bio-geochemical processes such as nitrogen fixation, chemolithoautotrophy, sulfate reduction and fermentation. Environmental perturbations that affect bacterial abundance or community composition are therefore likely to have large-scale effects on ecosystem function.

The traditional view of the marine carbon cycle was that eukaryotic organisms were the only important players in the transfer of carbon between trophic levels. Bacterial processes were largely ignored because bacteria were thought to be inactive and present in low numbers. It is now clear that this historical view of carbon flux from photosynthetic phytoplankton to herbivorous zooplankton to higher organisms is incomplete and the microbial loop needs to be considered in addition to this grazing food chain (Figure 5.3). This paradigm shift has come about over the past 30 years as

improvements in microbiological techniques for enumeration, measurement of growth and activity, and assessment of microbial diversity have revolutionised our understanding of marine microbiology[24]. It is now clear that organic flux into bacteria is a major pathway through which, on average, one-half of oceanic primary production passes[2,1].

Archaea were traditionally thought to be restricted to extreme environments but are now known to be highly abundant in sea water[22,34,25]. The Archaea comprise two major groups: the crenarchaeal Marine Group I, which dominates in deeper waters; and the euryarchaeal Marine Group II, which is more numerous in surface waters. Planktonic archaea are metabolically active and are able to take up inorganic carbon, contributing between 10 and 30 percent of total prokaryotic production in deep North Atlantic samples[48]. The physiology of archaea in the marine environment is still poorly understood, but there is indirect evidence that marine crenarchaeotes might be capable of ammonia oxidation and may therefore play a role in nitrogen cycling[99]. A recent study determined the natural distribution of radiocarbon in archaeal membrane lipids at two depths in the North Pacific, showing that the dominant metabolism at depth is autotrophy, whereas archaea in surface waters are predominantly heterotrophs[55]. Although many questions on archaeal metabolism remain unanswered, it is now clear that crenarchaea in the oceans play major roles in both carbon and nitrogen cycling[23]. The roles of pelagic archaea in the GBR have not yet been studied. However, it is likely that the GBR will have high numbers of the euryarchaeal Marine Group II archaea found in other shallow coastal regions.

The importance of marine viruses was not appreciated until the late 1980s but they are now known to be the most abundant biological entities in the sea. Bacteriophages cause bacterial mortality, creating a carbon cycle in which the dissolved organic matter assimilated by bacteria is released via bacterial lysis and metabolised by other bacteria, enhancing upper ocean respiration. Marine viruses are generally host specific and display a density-dependent mode of infection. Hence, they have considerable potential for altering bacterial community composition in the marine ecosystem. During algal blooms, marine viruses can infect the rapidly increasing population of algae, and viral lysis of microalgae can result in the release of large amounts of dimethylsulphide into the atmosphere[125]. Dimethylsulphide triggers cloud formation, illustrating yet another mode of marine microbe and climate interaction.

In addition to marine environments, benthic environments are also host to microbial communities. Benthic environments in the GBR include muddy and sandy sediments, coral rubble and rock surfaces. Nitrogen fixation has been reported to occur in coral reef sediments[15], with sediments surrounding Heron Reef containing ubiquitous and diverse nitrogen-fixing communities[49]. The total bacterial communities in sediments are diverse, and their composition is influenced by biotic and abiotic factors such as wave energy and sediment depth[49]. Sandy sediments in the vicinity of coral reefs can also contain high numbers of benthic microalgae[45]. Studies in these environments and similar environments in other ecosystems consistently find that benthic surfaces and sediments are colonised by complex and diverse bacterial and archaeal communities. Benthic microbial communities are important in nutrient cycling, particularly under anaerobic conditions within sediments. Cycling processes in anaerobic estuarine and coastal sediments can include anaerobic methane oxidation by archaea and anaerobic ammonia oxidation by planctomycete bacteria[97,94].

### *5.1.2.2 Symbiosis*

Symbiosis is considered a permanent association between organisms of different species. Marine microbes are involved in a variety of important symbiotic relationships with marine invertebrates from a range of taxa including sponges, cnidarians, molluscs, echinoderms and nematodes. Proposed symbiotic functions for marine microbes include: nutrition (through direct incorporation of dissolved organic matter in the sea water or translocation of photosynthate[121], quorum sensing[70], assistance with reproductive processes[61], assistance in chemical defence[101], contribution to structural rigidity[121], metabolism of a wide range of waste compounds[119], and production of secondary metabolites[85]. There are also many symbioses where the type of interaction between the host and its symbionts remains unknown. With such a broad range of functions, environmental conditions that affect the distribution or abundance of symbiotic marine microbes could have significant effects on host fitness and survival.

The best studied symbioses in GBR invertebrates are those between corals and their symbiotic zooxanthellae (Hoegh-Guldberg et al. chapter 10), and between sponges and their associated bacteria. In the case of sponges, more than 50 percent of the wet weight of the organism can be composed of bacteria. These are often remarkably complex symbioses with high microbial diversity, including novel species that have not been found in other ecosystems. There is evidence that some bacteria are ubiquitous in various sponges from different oceans and that some of the phylogenetic clades found in sponges are more similar to each other than to sequences found in other environments[47,30,51]. For example, the bacterial genus *Poribacteria* has so far been found only in sponges, and these microbes have less than 75 percent sequence homology to previously known bacteria[31]. Many studies also report that sponges contain distinct microbial communities not found in the surrounding sea water[108,47,95]. Taylor et al.[95] distinguished three types of sponge-associated bacteria: *specialists* found only on one host species, sponge associates found in multiple sponge species but not in sea water, and *generalists* from multiple hosts and the surrounding sea water.

In the intensively studied GBR sponge *Rhopaloeides odorabile*, the cultivated bacterial community is dominated by an alphaproteobacterium[108], close relatives of which were subsequently found in many other sponges from broad tropical locations[96,68,30]. However, the total microbial community in *R. odorabile* as detected by molecular techniques contains a great diversity of bacteria[110] as well as two archaea[109]. The roles of many of the symbionts in this sponge remain enigmatic, although the culturable alphaproteobacterium appears to be linked to sponge health[119]. In other GBR sponge symbioses, the role of microbial symbionts is better understood. Autotrophic cyanobacterial symbionts can contribute to host nutrition through extracellular lysis and phagocytosis[118] or by transfer of glycerol to sponge tissue[120]. Considering the predominance of bacteria within sponges, the complexity of these symbioses and the evidence for vertical transfer of some sponge symbionts through larvae[30,102], it seems likely that bacterial symbionts play vital roles for their host sponges. Shifts in these microbial communities due to climate change are therefore likely to affect sponge health, growth rates and capacity for defence from predation and fouling.

Corals are associated with an abundant microbiota in addition to the *Symbiodinium* symbiosis discussed elsewhere in this volume (Hoegh-Guldberg et al. chapter 10). This includes bacteria in the coral surface microlayer[83,69] and bacteria and fungi within the coral tissue[63,27,84]. A diverse assemblage of archaea (including representatives of both the crenarchaeotes and euryarchaeotes) are also

associated with corals[115]. The coral *Pocillopora damicornis* from the GBR contains a diverse bacterial assemblage dominated by *Gammaproteobacteria*, including some strains closely related to *Vibrio shiloi* and *Vibrio corallilyticus*[10], which are known causative agents of coral bleaching. As with sponges, there is some evidence that microbial populations associated with corals may be globally distributed[10] and may have beneficial effects for the corals[84]. If this is in fact the case, shifts in microbial communities caused by climate change are potentially an additional stressor for corals.

Microbial symbionts have been described in a range of other GBR invertebrates. The bivalve *Solemya terraeregina* from GBR reef sediments contain endosymbiotic bacteria in their gills[62]. The bacteria in *S. terraeregina* and in all other *Solemya* symbioses studied are *Gammaproteobacteria*, which are thought to fix $CO_2$ with energy obtained through the oxidation of reduced sulfur compounds. A marine gutless oligochaete from the GBR contains two bacterial endosymbionts just below the cuticle: a gammaproteobacterium that clustered with known chemoautotrophic endosymbionts, and an alphaproteobacterium and spirochaete distinctly different from all other chemoautotrophs[28]. Symbiotic bacteria are also thought to play a role in reproduction of the GBR nudibranch *Dendrodoris nigra*. Presence of symbiotic bacteria in the vestibular gland and egg masses of this nudibranch may be important in breaking down the mucus layer and egg capsule during intercapsular development[61].

### 5.1.2.3 Recruitment

For sessile animals such as corals, the choice of a suitable site for settlement is crucial for future survival. Physical and chemical cues are often critical factors in site selection for larval settlement[76, 50]. Micro-organisms can play an important role in the induction of settlement and metamorphosis in many marine invertebrates, including shellfish such as oysters and abalone[13], starfish[56], polychaete worms[100], hydroids[72] and corals[77,113]. The best known source of chemical cues for corals are the crustose coralline algae, but it is clear that bacterial biofilms can also produce settlement and metamorphic cues[46,41,77,113]. Marine biofilms have been reported to induce metamorphosis in several classes of cnidarians, including Anthozoa (hard and soft corals)[75,46,113], Scyphozoa (jellyfish)[11] and Hydrozoa[71]. Environmental conditions that adversely affect the distribution and abundance of microbes involved in settlement and metamorphosis of reef invertebrates could therefore have large-scale effects on ecosystem structure and the distribution and reproductive fitness of some keystone species.

### 5.1.2.4 Disease

In recent decades, there has been a global increase in reports of disease in marine organisms[67]. Disease epidemics have affected both vertebrate and invertebrate species including fish, seals, dolphins, shellfish (oysters, scallops, abalone and clams), starfish, sea urchins, sponges and corals (reviewed in Harvell et al.[44]). Disease outbreaks have also affected seagrass, kelp and coralline algae populations[44]. On the GBR, the incidence of disease has been most notable in corals[57,124,10] and sponges[112]. To date, at least eight different coral disease states have been described on the GBR, including pathogens that have had devastating effects on coral communities in the Caribbean (black band disease and white syndrome).

While it appears that the prevalence of marine disease has increased in recent years, this may be an artefact of increased awareness and detection. Determining whether prevalence is changing over time has been problematic due to an absence of baseline data for most marine organisms. Whether these reported disease outbreaks are due to new pathogens, changed environmental conditions or enhanced detection mechanisms is a topic of current debate. In any case, environmental stress such as climate change, which compromises the physiological fitness of marine invertebrates and their symbionts and provides enhanced conditions for disease-causing microbes, will likely increase the prevalence of disease in marine ecosystems.

To date, there are only six coral diseases for which the etiological agent has been described: bleaching of *Pocillopora damicornis* by the pathogen *Vibrio corallilyticus*[6], black band disease[18], white plague type II[82], aspergillosis[89,39], white pox[80], and bleaching of *Oculina patagonica* by *Vibrio shiloi*[64,65]. In contrast, there are numerous diseases and 'syndromes' for which no causative agent has yet been identified (reviewed in Richardson[81], Jones et al.[57], Bourne and Munn[10]). In fact, there is still some controversy about which species is responsible for forming the cyanobacterial mat in black band disease[18,32]. The potential role of viruses in coral disease is also being investigated. Heat-shocked corals have been shown to produce numerous virus-like particles that are evident in animal tissue, zooxanthellae and the surrounding sea water[21]. In addition, these virus-like particles appear to induce cell lysis in non-stressed corals, suggesting the presence of an infectious agent. However, unequivocal transmission electron microscopy evidence for this has yet to be obtained. On the GBR, virus-like particles are abundant and correlate with the spatial dynamics of the bacterioplankton community[86]. It has been suggested that virus-like particles on the GBR may significantly influence nutrient cycling rates and food-web structure[86].

Reports of global sponge disease have also increased dramatically in recent years (reviewed in Webster[114];[37,38,104,14,112]). These epidemics can have severe impacts on sponge populations and the ecology of reefs. Disease has decimated many sponge populations throughout the Mediterranean and Caribbean[38,104], and anecdotal reports suggest an increased prevalence of sponge disease on the GBR. However, a lack of baseline data makes it difficult to determine whether disease (which is a natural part of marine ecosystems) is actually increasing in prevalence. In almost all instances of sponge disease, the impact of infection on sponge tissue is described but there is a failure to isolate the causative agents. Putative pathogens have been identified for only two occurrences of sponge disease[9,112], and Koch's postulates have been confirmed in a single case[112]. Despite the ecological importance of sponges, the study of sponge disease is in its infancy.

A wide range of factors is thought to contribute to disease outbreaks in the marine ecosystem. These include increasing seawater temperatures associated with climate change, anthropogenic pollution, nutrient enrichment, overharvesting and introduced species. Concomitant increases in many of these factors on the GBR make it difficult to attribute shifts in disease prevalence to any particular factor. There is some evidence from the Australian Institute of Marine Science Long-term Monitoring Program that coral disease events on the GBR are more common following periods of coral bleaching, adding weight to the argument that stressed environments have less resilience to disease.

Another scenario that warrants consideration is that disease may increase in cases where the host is particularly successful, and increases in host numbers result in an increased rate of contact between the infectious agent and its host. Conversely, reductions in the host population can result in the complete disappearance of diseases that are highly specific for that host[67].

### 5.1.3 Critical factors for marine microbes

Marine microbes respond very rapidly to changing environmental conditions, making them ideal bio-indicator organisms. Many prokaryotes also have the ability to rapidly evolve and respond to small perturbations in temperature by the expression of temperature-regulated genes. This has significant implications for resilience and pathogen virulence. Marine microbes also have strict physiological thresholds that make them sensitive to small perturbations in temperature, nutrients, salinity, oxygen and a range of anthropogenic contaminants. For these reasons, micro-organisms are ideal indicators for alerting us to climate change and other anthropogenic stressors in the marine ecosystem.

## 5.2 Vulnerability of marine microbes to climate change

### 5.2.1 Changes in El Niño Southern Oscillation and ocean circulation

Many marine pelagic microbes are ubiquitous in the ocean[26], hence, changes to oceanic circulation (such as a southern extension of the East Australian Current) are not expected to have significant direct impacts on populations. However, a shift in the geographic range of some GBR microbial populations may occur.

### 5.2.2 Changes in water temperature

#### *5.2.2.1 Exposure – water temperature*

The level of exposure to changing oceanic temperatures varies for different microbial niches. Pelagic microbes are highly exposed to even slight temperature shifts. However, some members of the benthic community (including microbes within biofilms) may be buffered from temperature shifts by virtue of their physical location beneath sediment or other organisms. Likewise, symbiotic and pathogenic microbes may be less exposed to changes in seawater temperature due to their location within host tissue.

#### *5.2.2.2 Sensitivity – water temperature*

The sensitivity to temperature of most pelagic, benthic and symbiotic microbes is extremely difficult to assess. Since precise temperature thresholds are known for only a few cultivated species, it is not possible to describe the sensitivity of the GBR microbial ecosystem as a whole. However, the sensitivity of pathogenic microbes to elevated temperatures has received considerable research attention. Elevated seawater temperatures can affect the frequency and severity of disease outbreaks by increasing the prevalence and virulence of pathogens, facilitating invasions of new pathogens or reducing host resistance and resilience[91]. In particular, increased seawater temperature could potentially affect the overall health of marine organisms, thereby contributing to an increased or decreased incidence of disease on the GBR. Also, as temperatures increase, oxygen levels decrease and metabolic rates increase, potentially leading to additional respiratory stress in some organisms. It is interesting that disease outbreaks appear to be caused by so many different types of pathogens – viruses, bacteria, fungi and parasites – suggesting that the increased incidence of disease associated with higher seawater temperature is potentially linked to a reduction in the health of the host organisms.

Alternatively, increasing temperatures may alter the virulence mechanisms of a pathogen, as is seen with the coral pathogen *Vibrio shiloi*. A great deal of research has been directed towards describing the virulence of this coral pathogen[98,7,3,4,5]. These studies have characterised a wide range of virulence mechanisms that are stimulated under elevated seawater temperatures. These include chemotaxis and adhesion to a beta-galactoside receptor in the coral mucus, penetration into epidermal cells, differentiation into a viable-but-not-culturable state, intracellular multiplication, production of toxins that inhibit photosynthesis, and production of superoxide dismutase to protect the pathogen from oxidative stress.

In sponges, it is possible that under adverse environmental conditions, such as high temperature and reduced water flow, normally non-pathogenic bacteria become capable of spongin degradation within live tissue[37]. The removal of bacteria and sponge excretion products by passive and active ventilation could also be reduced, facilitating bacterial proliferation and the onset of disease. Under conditions of high seawater temperatures and reduced water flow, sponge pathogens may switch on virulence mechanisms, sponges may be unable to control proliferation of bacteria[104], or degeneration of sponge tissue may occur when exogenous bacteria replace the associated populations[103,37].

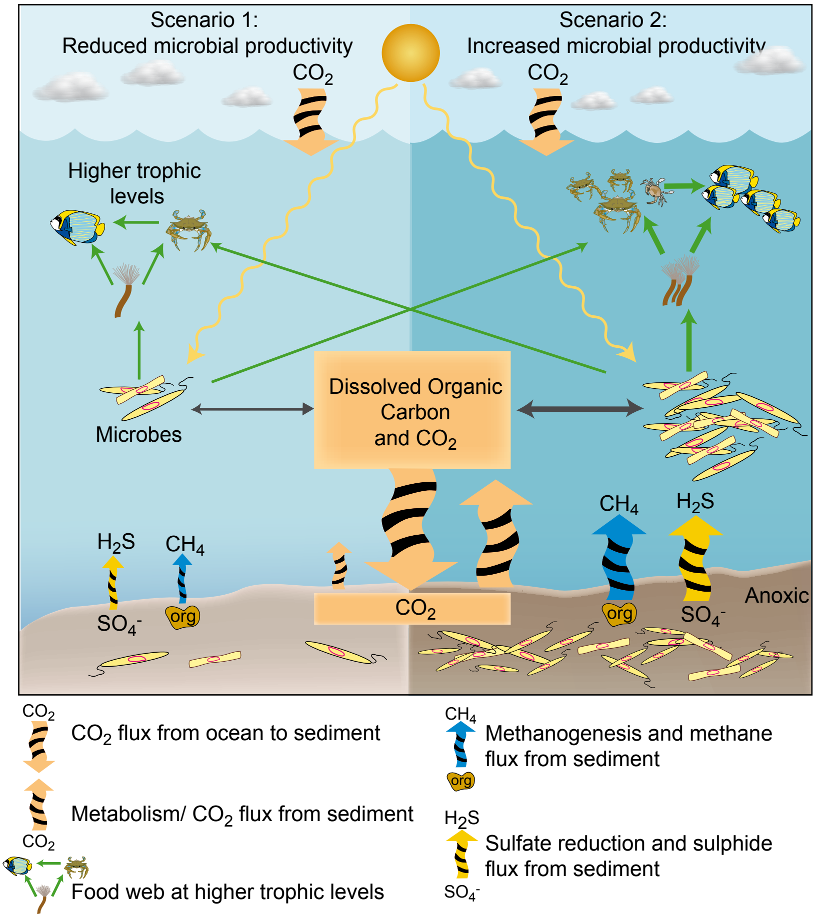
### *5.2.2.3 Impacts – water temperature*

#### Nutrient cycle

An increase in seawater temperature of 1 to 2°C may have profound effects on the microbial loop. The composition of the microbial community is likely to undergo shifts in both numbers and species of bacteria that will affect the rates of carbon cycling in ways that we are not yet able to predict (Figure 5.4). For example, one can envision a scenario where a slight increase in water temperature in the GBR causes an increase in numbers and activity of pelagic bacteria, resulting in greater amounts of carbon passing through the microbial loop, and a concomitant reduction in carbon passing to higher trophic levels resulting in a reduction in fish numbers. A similar example from the eastern Mediterranean cites fish production being diminished by a dominant microbial loop[122]. Reduced numbers of fish that graze on macroalgae could ultimately result in a transition from coral-dominated to algal-dominated communities. Conversely, an increase in temperature may cause a shift to a less efficient bacterial community and a lower flux of carbon through the microbial loop with potentially the opposite effect on fish populations. The important point is that bacterial communities may be rapidly and profoundly affected by small shifts in temperature, with potentially major consequences for other reef organisms because of the importance of bacterial communities in carbon flux through the ecosystem.

If increased seawater temperature caused an increase in benthic bacterial productivity, there could be a concomitant increase in anaerobic processes as available oxygen is rapidly utilised (Figure 5.4). Since methanogenic archaea are present in anaerobic sediments, there is also the potential for an increase in methanogenesis if anaerobic zones in sediments are extended. This, in turn, would increase the total production of methane, which could be utilised by other microbes or fed back into the climate change cycle. Anaerobic methane oxidation is a process of global importance in marine sediments[106] and is performed by at least two phylogenetically distinct groups of archaea that are often observed in consortia with sulfate-reducing bacteria[105].

***Figure* 5.4** *Potential productivity scenarios associated with climate change conditions*



The long-term burial of organic carbon in sediments results in a net accumulation of oxygen in the atmosphere, thereby mediating climate change conditions[117]. Sediment microbial activity can play a fundamental role in determining whether particulate organic carbon is recycled or buried. Temperature regulation of the processes that lead to the microbial breakdown of complex particulate organic carbon could therefore influence the rates of overall carbon mineralisation. A study that examined carbon cycling in coastal anaerobic sediments reported a variable temperature response of the key functional microbial groups that mediate organic matter mineralisation[117]. In particular, the authors detected a temperature sensitivity of sulfate-reducing bacteria (whose activity dominates the anaerobic terminal metabolic pathway in marine sediments) greater than the temperature sensitivity of microbes involved in the hydrolysis/fermentation of complex organic matter[117]. This pioneering study showed that microbial processes involved in organic carbon breakdown were extremely sensitive to small changes in temperature, suggesting that global climate change may significantly influence the efficiency of organic carbon recycling in coastal ecosystems. While these results pertain to a temperate ecosystem, it is conceivable that GBR microbes could respond in a similar way. However, knowledge of microbial community composition and temperature thresholds of individual species in GBR sediments is currently too limited to predict the response of key functional groups involved in organic carbon cycling.

### Recruitment processes

Changes in microbial communities due to a 1 to 2°C increase in water temperature may alter production of morphogenic signalling compounds or responses of larvae to these compounds, which may have an effect on patterns of larval settlement and subsequent distribution of invertebrates. Alternatively, shifts in the community composition of benthic biofilms could adversely or positively affect microbial succession and subsequent recruitment of macro-organisms. This would have obvious implications for reef-building, maintenance and recovery processes. Limited knowledge of these processes and their probable complexity make it unlikely that these effects will be predictable.

### Symbiosis

Considerable attention has been directed towards the impact of elevated seawater temperature on the symbiotic relationship between corals and zooxanthellae. However, almost no research currently exists on the impact of increasing seawater temperature on other reef microbial symbioses. It is likely that microbial symbionts have strict temperature thresholds, and a breakdown in symbiosis could result in host mortality, reduced host fitness, shifts in host geographic range, increased disease or an increase in predation or grazing. There is also the possibility that increased seawater temperatures may cause a shift from symbiotic to pathogenic function for some species.

### Disease

Diseases have the potential to cause major impacts on population levels, biodiversity and community structure of coral reefs by causing shifts in the abundance of various groups. For example, in the GBR it is the fast-growing branching coral species (specifically the acroporids and pocilloporids) that are most susceptible to disease[124]. In the Caribbean, populations of *Acropora palmata* were highly susceptible to disease in the 1980s, whereas the massive reef-building corals are currently most vulnerable to disease epidemics[67]. Corals with varying morphologies provide different habitats for many different reef organisms, and an increase in disease occurrence in one morphological group could lead to dramatic changes in reef communities. A classic example of a complete phase shift in community structure as a result of disease happened in the Caribbean, where a disease epidemic in the dominant herbivore, the sea urchin *Diadema antillarum*, by an unidentified pathogen caused a shift from coral-dominated to algal-dominated reefs[53].

Elevated seawater temperature associated with El Niño – Southern Oscillation (ENSO) events has been implicated in interannual variation of Dermo disease in the Gulf of Mexico (a disease of the oyster *Crassostrea virginica* caused by the protozoan parasite *Perkinsus marinus*)[59]. Dermo disease closely follows the ENSO cycle, with prevalence and infection intensity declining during El Niño events (cold, wet conditions) and rising during La Niña events (warm, dry conditions). This relationship between Dermo epidemics and ENSO suggests that it may be possible to predict disease outbreaks with climatic models, which could provide potential management strategies for oyster populations. Unfortunately, our current disease epidemiology datasets for the GBR (initiated for corals in 1998) are not yet extensive enough for valid correlations to be made with the ENSO cycle.

Predictions of how disease will affect marine communities are also complicated by the fact that stressors (such as increased temperature) may sometimes have a more negative impact on the pathogen than on the host[66], a scenario that would facilitate recovery of infected populations. It is therefore important to acknowledge that changing environmental conditions may increase or decrease the occurrence of disease.

At this point, it would be pertinent to briefly discuss the influence of climate on the abundance and ecology of human pathogens, which are ubiquitous in the marine environment, including the GBR. Pathogenic *Vibrio* species are responsible for the majority of non-viral infections related to shellfish consumption[126]. Pathogenic vibrios thrive in warm waters of moderate salinity[87] and are closely associated with aquatic invertebrates[73]. Altered climatic conditions may cause a shift in the geographic range of these pathogens, potentially resulting in increased risk of infection for humans. In addition, changes in plankton populations (in which vibrios are often commensals) would similarly affect the ecology of these pathogens. Ecological models have been developed to define the role of climate-related variables in outbreaks of cholera[54,17,74,79]. These suggest that abiotic conditions including temperature, pH, salinity, $Fe^{3+}$ and sunlight all favour the growth of *V. cholerae* and/or host plankton and result in increased pathogen virulence. Predicted climate change conditions such as elevated seawater temperature could potentially select for an increased prevalence or virulence of human pathogens in the GBR region.

### 5.2.2.4 Adaptive capacity – water temperature

The 'rare biosphere' of bacteria recently identified by Sogin et al.[90] may provide some resilience to environmental change. The enormous diversity of low-abundance populations suggests that there should be some capacity to take over ecological niches that become available due to environmental perturbations. Several ecological models predict a survival advantage for rare species since they are less affected by predation and direct competition with dominant species. As noted by Sogin et al.[90], the rare biosphere could 'explain how microbial communities recover from environmental catastrophe'.

#### Pelagic and benthic microbes

There is the possibility of a shift in geographic range with an export of tropically acclimated species to southern temperate reef environments. Alternatively, microbes that are present as minor constituents of the total community could become major players if they are better adapted to new temperature regimes. As different microbes come to dominate the waters and sediments, shifts in the overall patterns of carbon and nitrogen cycling are conceivable. Given our current state of knowledge, it is not possible to predict the consequences of shifts in communities of bacteria and archaea in the water column and sediments.

#### Symbiosis

The high specificity of symbiotic microbial–invertebrate associations has been demonstrated by experiments with the bobtail squid *Euprymna scolopes*. This species of squid shows a preference for *V. fischeri* strains isolated from itself rather than from other species of squid or from the water column[78]. This shows that intra-species variation can be important in these complex and subtle invertebrate–bacterium symbioses and that adaptive capacity would be considered low for such intimate relationships. It is also possible that vertically transmitted symbionts may find refuge within their hosts in the face of elevated seawater temperature since they may be relatively immune from competition with bacteria in the surrounding seawater milieu. Of course, if the hosts are particularly susceptible to changing conditions and become extinct as a result of increased seawater temperature, vertically transmitted symbionts may be 'trapped' within the declining populations of the host and follow the host into extinction.

#### *5.2.2.5 Vulnerability and thresholds – water temperature*

The diverse and active microbial community has a major impact on nutrient cycling in marine waters. Small shifts in community composition could result in large changes in nutrient cycling. Increased seawater temperature could have significant impacts on microbial community composition and ecosystem function in the pelagic and benthic environments and affect the wide range of symbiotic and pathogenic relationships that currently exist on the GBR. However, the complexity of marine microbial communities and the nature of their interactions with nutrients make it impossible to predict the consequences of an increase in temperature of 1 to 2°C in waters of the GBR.

Despite the vulnerability of pelagic, benthic, symbiotic and pathogenic microbes to temperature, some resilience could potentially be conferred to the ecosystem by rapid genetic turnover, functional redundancy, expression of temperature-regulated genes and lateral gene transfer. Gene transfer is an important mechanism by which microbes can interact in the environment and facilitates the exchange of DNA that transforms other bacterial cells and enables populations to adapt or evolve. Prokaryotes have several possibilities to transfer genes including transduction, where genes are transferred by the activity of viruses. This results in the horizontal spread of genes within a community and may contribute to diversity. The 'insurance hypothesis' assumes that there are many species in an ecosystem that can perform the same or very similar functions[127]. These redundant species can take over ecosystem functions once a dominant species becomes extinct or functionally obsolete. This insurance due to redundancy of species may result in a resilience of ecosystem functions. However, to date there is very little direct evidence of functional redundancy in the marine ecosystem.

### 5.2.3 Changes in ocean chemistry

#### *5.2.3.1 Exposure – pH*

As outlined for seawater temperature, most marine microbes would be highly exposed to changes in seawater chemistry.

#### *5.2.3.2 Sensitivity – pH*

The sensitivity of marine microbes to changes in pH has been examined primarily by observing growth rates and survival in a few cultivated species. The sensitivity of entire microbial communities, including effects of pH on microbial processes, requires further research to be fully elucidated.

#### *5.2.3.3 Impacts – pH*

Variable effects of reduced pH on marine micro-organisms have been reported.

Research studying the effects of $CO_2$ induced seawater acidification on the growth rates of marine microbes found that bacteria were so resistant to high concentrations of $CO_2$ that drastic impacts in terms of growth were observed only under conditions where the pH was below 5.5 to 6.0[93]. The GBR is unlikely to experience a pH lower than 6.0 in the foreseeable future. These data suggest that the impacts of ocean chemistry on marine micro-organisms should be minimal or negligible. However, the study by Takeuchi et al.[93] focused on the effects of pH on bacterial growth rates but not on specific transformations that are mediated by marine micro-organisms (such as the nitrogen cycle).

Acidifying sea water causes an increase in the concentration of ammonium ions and a decrease in concentrations of ammonia. Ammonia-oxidising micro-organisms are central to the nitrogen cycle and will be adversely affected by acidification because they cannot oxidise the ammonium ions. This will have subsequent effects on the denitrifying and nitrifying bacteria in the marine ecosystem. There is evidence that marine nitrification rates are significantly reduced as sea water becomes more acidic[118,107,36], and the large-scale inhibition of nitrification and subsequent reduction of nitrite and nitrate concentrations could result in a decrease in denitrification. This, in turn, could lead to a build-up of nitrogen and unpredictable eutrophication phenomena.

### *5.2.3.4 Adaptive capacity – pH*

The direct effect of pH on fundamental microbial processes (such as the nitrogen cycle) suggests that the adaptive capacity of the microbial system to pH will be quite low. However, further research on the impacts of acidification on microbial community dynamics and microbial function is required before this can be fully determined.

### *5.2.3.5 Vulnerability and thresholds – pH*

The projected decline of 0.4 to 0.5 in ocean pH in the GBR by 2100 could have significant consequences on ecosystem function related to a direct impact on the nitrogen cycle and microbial loop. In addition, if important keystone microbial species are particularly sensitive and experience a shift in abundance or function due to altered ocean chemistry, this would obviously have larger implications for the wider microbial and tropical marine ecosystems.

## 5.2.4 Changes in light and ultraviolet light

Ultraviolet light is a powerful mutagen, interfering with accurate DNA replication and introducing errors during the cellular processes undertaken during DNA repair. A study that examined the effects of ultraviolet (UV) exposure on natural Antarctic phytoplankton and protozoans found that UV radiation altered the biomass and species composition of the community[20]. The changes to size and availability of food to higher trophic levels could have major consequences by changing food-web structure and function and potentially influencing biogeochemical cycles. The expected increases in UV radiation with climate change could potentially impact on GBR microbial communities by increasing the rate of genetic change or causing shifts in community composition, with a decline in UV-sensitive species and an increased abundance of UV-tolerant species. This could have significant implications for the microbial loop and for pathogenic and symbiotic relationships (as identified in section 5.2.2.3).

### 5.2.5 Sea level rise

A rise of 0.1 to 0.9 metres in sea level by 2100 could increase fluxes of nutrients and pollutants into the marine environment and have direct impacts upon microbial communities as outlined in section 5.2.7. In addition, a rising sea level may facilitate the introduction of new microbes from terrestrial sources into the ecosystem. For example, *Aspergillus sydowii*, a pathogen of sea fans that has caused significant mortality in the Caribbean, has been identified in African dust samples transported thousands of kilometres from the Sahara to the Caribbean[116].

### 5.2.6 Physical disturbance – tropical storms

Predicted increases in cyclone intensity could affect GBR microbial populations due to increased resuspension of bottom sediments and associated carbon and nutrients. This will have a direct impact upon the microbial loop (see section 5.2.7).

### 5.2.7 Rainfall and river flood plumes

#### *5.2.7.1 Exposure – terrestrial inputs*

It is foreseeable that more extreme flood events will increase nutrient and contaminant runoff into inshore areas, potentially altering microbial community composition and function.

#### *5.2.7.2 Sensitivity – terrestrial inputs*

Nitrogen stimulates pelagic microbial growth and thus has the capacity to influence photosynthetic rates and carbon dioxide levels. An increased concentration of nitrogen entering the GBR via river runoff and eutrophication would have significant implications for both micro and macro communities due to impacts on the microbial loop, symbiotic relationships and disease processes.

#### *5.2.7.3 Impacts – terrestrial inputs*

The nature of impacts from increased terrestrial inputs is extremely difficult to predict or model because of the complexity of the bacterial community. Bacterial activity can modify organic material even without large fluxes of organic material into bacteria[1]. For example, the activity of slow-growing bacteria on the surfaces of small particulate material, termed 'marine snow', can result in production of large amounts of ectohydrolase enzymes that efficiently solubilise the organic particulate matter, releasing it into the surrounding water and reducing the sinking flux of carbon into deeper waters[88]. A small shift in nutrient concentrations may change the bacterial communities performing this activity and select for communities that are either more or less efficient at this uncoupled solubilisation, with resultant changes in the flux of carbon through marine ecosystems even without marked changes in bacterial numbers or activities.

Similarly, the work of Bidle et al.[8] showed that bacteria play an important role in solubilisation of silica from diatoms, thereby affecting the availability of free silica for new diatom growth. Some bacteria produce potent proteases that result in higher rates of silica dissolution and less transport of silica into the deep benthos, potentially resulting in higher diatom growth in the photic zone and greater rates of photosynthesis. Once again, a small shift in the bacterial communities, to favour bacteria with higher or lower rates of silica dissolution, could have profound effects on carbon cycling.

Nutrient enrichment may also increase the incidence and severity of marine epizootics, as evidenced by an increase in the severity of coral disease in the Caribbean after increased nutrient exposure[12]. Increases in the concentration of inorganic nitrogen and phosphorous could affect disease dynamics by increasing pathogen fitness and virulence[59] or negatively impacting on host immunity.

### *5.2.7.4 Adaptive capacity – terrestrial inputs*

In the microbial system, responses to terrestrial inputs could include changes in species composition, changes in growth rates, changes in gene expression, changes in physiological (enzyme) activity and changes in intimate associations (symbiosis and pathogens) with other organisms. Multiple species may fill similar physiological niches in the marine environment; hence, there is some potential for microbial community adaptation. However, for more-specific intimate associations such as those with symbionts and pathogens, it is impossible to predict the adaptive capacity with our current limited state of knowledge of these relationships.

### *5.2.7.5 Vulnerability and thresholds – terrestrial inputs*

The complexity of the marine microbial loop, our limited knowledge of microbial associations with other reef organisms, and a lack of data on species or community thresholds make it impossible to assess the vulnerability and thresholds of GBR microbial communities to increased terrestrial input.

## 5.2.8 Linkages with other ecosystem components

### *5.2.8.1 Constraints to adaptation*

With such limited data on how marine microbial communities respond to climate change parameters, it is difficult to accurately assess the overall constraints to adaptation. However, it would be reasonable to assume that concurrent stressors would have a more detrimental impact on the ecosystem and potentially constrain the adaptive capacity of marine micro-organisms. The high sensitivity and relatively short generation times of most marine microbes suggest that, in the absence of multiple stressors, microbes will be better able to adapt to chronic than to acute environmental perturbations.

### *5.2.8.2 Interactions between stressors*

The complexity of the microbial loop and a lack of data on the functional role of many microbial species limit our ability to reliably assess the impacts of multiple stressors on GBR microbial communities. However, a study examining the effects of copper on a GBR sponge species showed that the community structure of sponge-associated bacteria was negatively affected by elevated copper concentrations and that a shift in the symbiotic community potentially caused a decline in sponge health[111]. Although this is yet to be examined, it is foreseeable that increased seawater temperature and elevated nutrients and contaminants from river discharge could have similar and compounding effects on microbial symbioses and other GBR microbial communities.

### *5.2.8.3 Threats to resilience*

Concurrent stressors are probably the most foreseeable threat to ecosystem resilience. For example, an increase in seawater temperature or nutrient load as a result of climate change has a detrimental effect on the health of many invertebrate species, making them more susceptible to disease and increasing the potential for opportunistic bacterial species to become pathogenic. Other threats to resilience could include the introduction of pesticides or contaminants that impact on benthic microbial processes, and the introduction of new pathogens causing disease outbreaks.

## 5.3 Summary and recommendations

### 5.3.1 Major vulnerabilities to climate change

The projected increases in sea temperature, ocean acidification and terrestrial input are likely to be the primary climate change factors that will significantly impact marine microbial assemblages. The predicted impacts of these environmental shifts include changes to microbial community composition and function that may have significant implications for cycling within the microbial loop, recruitment, symbiotic relationships and disease. These are likely to have flow-on effects to higher trophic levels in the tropical marine ecosystem.

### 5.3.2 Potential management responses

In view of microbial abundance, diversity, interactions with reef invertebrates and influence on ocean chemistry, it is essential that ecosystem-based conservation models begin to incorporate micro-organisms.

While the effects of increased sea temperature will be difficult to mitigate from a GBR management perspective, there are a range of contributing environmental variables that could be amenable to management intervention. In addition to temperature-induced stress, marine microbial communities can be highly susceptible to other forms of anthropogenic pollution (such as elevated trace metals and nutrients). To illustrate this, case studies of copper-sensitive symbiotic microbes from a GBR sponge and the increased severity of coral disease under elevated nutrients were outlined. These examples highlight the importance of management strategies that aim to minimise stress to marine organisms (such as improving water quality and reducing nutrient loads). It is possible that this type of management approach could reduce the risk of disease outbreaks and the breakdown of symbiotic relationships in reef invertebrates.

### 5.3.3 Further research

As discussed in a recent review by DeLong and Karl[24], ‘a mechanistic understanding of the susceptibility of marine ecosystems to global environmental variability will require a comprehensive description of … marine physical, chemical and biological interactions including thresholds, negative and positive feedback mechanisms and other nonlinear interactions’. In recent years, there have been important discoveries of previously unknown microbes, many of which have a significant impact on oceanic processes[40,35,43]. An inadequate understanding of basic microbial community composition and function in the GBR means that considerable research effort is required to begin to accurately assess the effects of environmental change on pelagic, benthic, symbiotic and pathogenic microbes.

In particular, research priorities for the GBR should include:

1) **Examination of microbial processes** – including examining the role of microbes in carbon and nitrogen cycles.
2) **Examination of disease processes** – including examining disease aetiology and pathogen virulence so that managers can understand the conditions that promote the onset and transmission of disease.
3) **Examination of the effects of climate change conditions on microbial symbioses** – including examining the functional role of microbial symbionts and individual species thresholds so that the vulnerability of reef organisms to climate change can be comprehensively assessed.
4) **Examination of the effects of climate change conditions on biofilm formation** – including examining the role of biofilms in biogeochemical processes and metamorphic signaling to reef invertebrates.
5) **Metagenome sequencing of GBR seawater and sediment microbes** – such sequencing would facilitate the development of a comprehensive list of microbial inhabitants and their physiological potential, revealing patterns of biochemical interactions and habitat-specific correlations that could not be obtained by analysis of individual species. Most importantly, metagenome sequencing would assist interpretation of the evolutionary processes driving microbial adaptation and provide greater insight into how the microbial community is adapting to climate change.

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**Part II: Species and species groups**

# Chapter 6

## Vulnerability of Great Barrier Reef plankton to climate change

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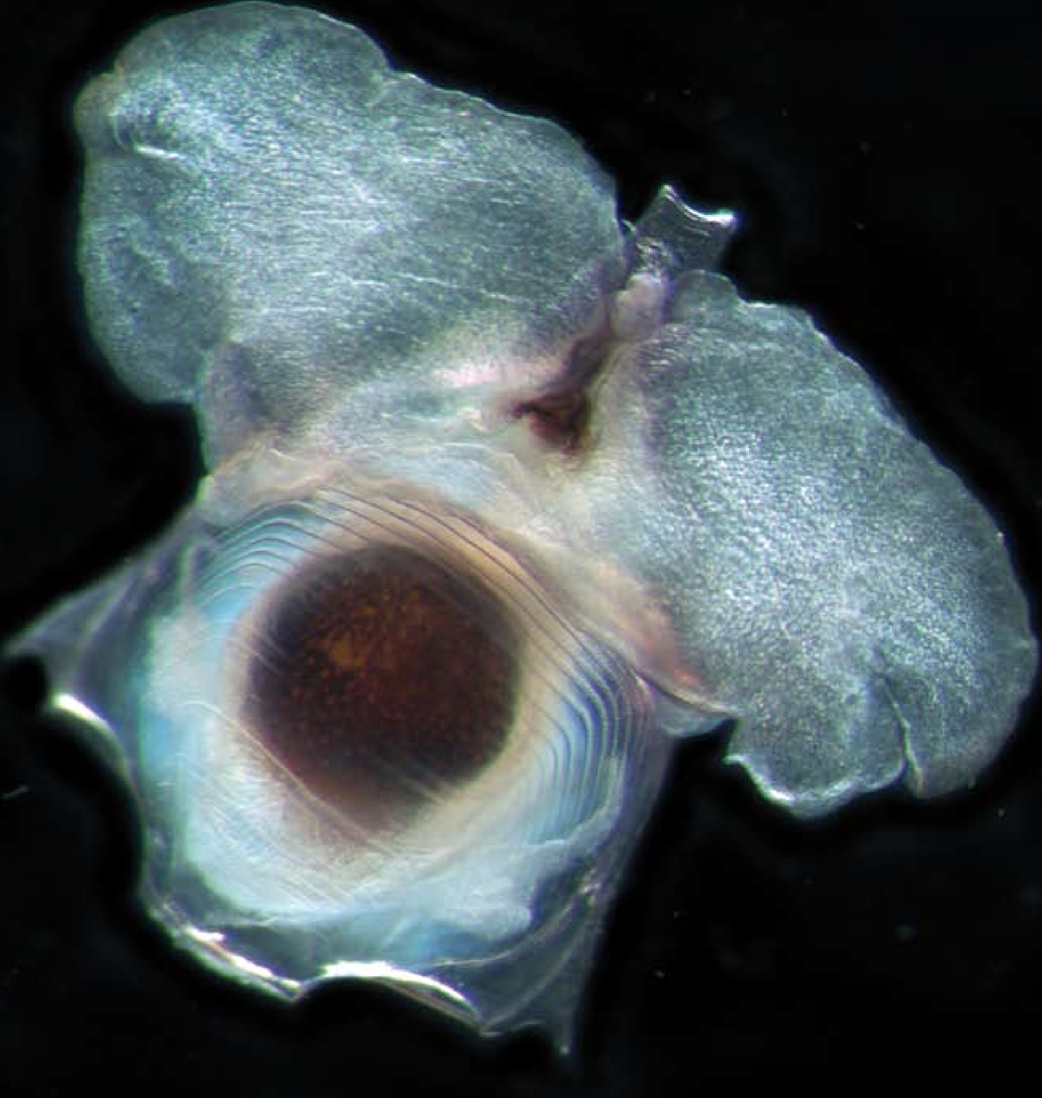


The pteropod *Cavolinia longirostris* is threatened by acidification of Great Barrier Reef waters.
Image courtesy of Russ Hopcroft, University of Alaska, Fairbanks (c) 2007

## 6.1 Introduction

Published observations of plankton within the Great Barrier Reef (GBR) date back to Captain Cook's northward passage through the lagoon, when he reported extensive 'blooms' of unknown origin. His ship log entry for August 28 1770 reads:

> *The sea in many places is here cover'd with a kind of brown scum, such as sailors generally call spawn; upon our first seeing it, it alarm'd us thinking that we were amongst Shoals, but we found the same depth of water where it was as in other places. Neither Mr Banks nor Dr Solander could tell what it was although they had of it to examine.*

These were undoubtedly blooms of *Trichodesmium*[8]. However, it was not until the Great Barrier Reef Expedition of 1928 to 1929 that the first and only significant study of plankton in the region was undertaken[74,100,29]. Unfortunately, since then, there has been little emphasis placed on documenting and understanding the biodiversity and processes within plankton communities of the GBR.

Our approach here is to examine potential ways that climate change may alter plankton communities of the GBR in the future, focusing on the physical mechanisms that currently drive plankton productivity and composition. Many of the oceanographic and climatic features of the western Coral Sea and GBR region and the ways in which they may be influenced by climate change are detailed in Steinberg (see chapter 3). Smaller members of the plankton such as the viruses and bacteria are covered by Webster and Hill (see chapter 5). Key reef-associated organisms with planktonic life stages such as crown-of-thorns starfish, corals, fish and jellyfish, as well as the ecosystem-level responses such as their recruitment and patch connectivity, will be covered by Kingsford and Welch (see chapter 18). Since there are no long time series of plankton data for waters of the GBR for assessing climate-related trends and their drivers, and few detailed studies in the laboratory or in the field, this review necessarily draws on relevant knowledge from other ecosystems, tropical where possible, and others when required.

### 6.1.1 Plankton

Plankton is a generic term describing organisms that have limited locomotive ability relative to the water bodies in which they live. A variety of organisms live in the plankton, ranging in size from viruses (femtoplankton) to large jellyfish (megazooplankton). Table 6.1 shows size classes of plankton in aquatic ecosystems, with some of their important members in GBR waters mentioned in the text.

Tropical plankton communities are highly diverse, containing organisms from almost all kingdoms, phyla and families. These organisms use their environment, its resources, and each other, in a wide variety of ways. The most common way to classify planktonic organisms is on the basis of size, which affects sinking, light utilisation, mobility and trophic status. Organisms with particular functional roles in the ecosystem (eg grazers and nitrogen-fixers) occur in a number of size classes, though in general primary producers tend to be smaller than grazers, which tend to be smaller than predators.

*Table 6.1* *Size classes of plankton in aquatic ecosystems[67]. Sizes are reported in µm (micrometres) and mm (millimetres)*

| Size class | Size range | Representative organisms | Functional groupings |
|---|---|---|---|
| Femtoplankton | Less than 0.2 µm | Viruses | Parasites |
| Picoplankton | 0.2 to 2 µm | Archaea, bacteria, cyanobacteria (eg *Synechococcus*), Prochlorophytes (eg *Prochlorococcus*) | Primary producers, saprophytic heterotrophs, nitrogen-fixers |
| Nanoplankton | 2 to 20 µm | Cyanobacteria, diatoms, flagellates (autotrophic, heterotrophic) | Primary producers, grazers, predators, nitrogen-fixers |
| Microplankton | 20 to 200 µm | Ciliates (including foraminifera), coccolithophores, diatoms, dinoflagellates, copepod juveniles | Primary producers, grazers, predators |
| Mesoplankton | 0.2 to 20 mm | Amphipods, appendicularians, chaetognaths, copepods, cyanobacteria (eg *Trichodesmium* colonies), thaliaceans (doliolids and salps) | Primary producers, grazers, predators, nitrogen-fixers |
| Macroplankton | 20 to 200 mm | Euphausiids, heteropods, jellyfish, larval fish, mysids, pteropods (eg *Cavolinia longirostris*), solitary salps | Grazers, predators |
| Megaplankton | Greater than 200 mm | Jellyfish, colonial salps | Grazers, predators, primary producers |

This chapter focuses on the best studied plankton, primarily the phytoplankton and mesozooplankton. Key groups within the phytoplankton that we discuss are the cyanobacteria, dinoflagellates and diatoms. Within the mesozooplankton, we concentrate on the copepods, because this has been the most studied group and they are numerically the most abundant. Copepods constitute 63 percent of mesozooplankton abundance on tropical continental shelves[72], and somewhat more, about 80 percent, in the waters of the GBR[70].

### 6.1.1.1 Biodiversity

Phytoplankton communities in the GBR ecosystem are diverse and cosmopolitan in character, comprising a mixture of oceanic forms with global pan-tropical distributions, and assemblages of diatoms and dinoflagellates[109] found in coastal and upwelling regions worldwide. There are no known phytoplankton species endemic to the GBR. A three-year survey of the microphytoplankton in the 1970s produced a species list of 220 diatoms and 176 dinoflagellates[93]. The colonial nitrogen-fixing cyanobacterium *Trichodesmium* episodically accounted for a significant proportion of the microphytoplankton in lagoon samples, with abundances inversely correlated with those of diatoms[92].

Recent studies using size fractionation of phytoplankton communities show that phytoplankton biomass and productivity are dominated by picoplankton-sized organisms, such as the phototrophic cyanobacteria *Synechococcus* (approximately 1 to 2 micrometres) and *Prochlorococcus* (approximately 0.6 micrometres[36,19,20,21]. Both of these genera are present as genetically identifiable, physiologically adapted strains[82,45] rather than as morphologically identifiable species.

Zooplankton communities in GBR waters are similar to those of other tropical or subtropical coasts, and may include endemic species in bays and estuaries[78,79]. Copepods are the most speciose group of zooplankton in the GBR (Table 6.2). The most comprehensive species list for the zooplankton of the GBR is from a study nearly 80 years ago, where Farran[29] identified 193 species of pelagic copepods. However, such early plankton studies used nets with mesh sizes greater than 200 micrometres, as widely recommended for northern temperate plankton, but which miss the numerically dominant and smaller (less than 200 micrometres) copepod species in GBR waters (eg *Parvocalanus crassirostris*, *Oithona attenuata* and *O. nana*). Based on collections with nets of finer mesh, McKinnon et al.[81] added a further 11 species of small copepods.

***Table 6.2*** *Meso- and macrozooplankton biodiversity recorded by the Great Barrier Reef Expedition of 1928 to 1929*

| Taxon | Number of species |
|---|---|
| Siphonophora[110] | 32 |
| Doliolida[100] | 3 |
| Salpida[100] | 6 |
| Appendicularia[100] | 8 |
| Pteropoda (Thecosomata and Gymnosomata)[100] | 15 |
| Heteropoda[100] | 3 |
| Mysidiacea[108] | 23 |
| Euphausiacea[108] | 14 |
| Copepoda[29] | 193 |
| Chaetognatha[17] | 12 |

Reef-associated zooplankton assemblages comprise a mixture of open-water and demersal or emergent species, such as amphipods, cumaceans, decapods, mysids, ostracods and polychaete worms[107,111]. Larger zooplankton, such as the pteropods *Creseis* spp. and *Cavolinia longirostris*, are also present, and are particularly abundant in December and January respectively[100]. Salps (Thaliacea) can occur sporadically in great abundance[100].

### 6.1.1.2 Distribution across the GBR

Phytoplankton studies spanning the width of the GBR ecosystem have demonstrated a strong onshore–offshore gradient. Communities in nearshore waters are morre frequently dominated by diatoms[93] because of more consistent nutrient inputs and greater nutrient availability from adjacent terrestrial sources and shallow sediments. Diatom-dominated assemblages within GBR waters are therefore

diagnostic of enhanced or persistent nutrient inputs into a region. Diatoms achieve dominance after disturbances, for brief periods at least, because they have faster intrinsic growth rates[32] than picoplanktonic cyanobacteria[34]. The difference in response times between the flagellate grazers of picoplankton (days) and the metazoan grazers of microplankton diatoms (weeks) also contributes to the persistence of diatom blooms. By contrast, communities in oligotrophic (low nutrient) outer-shelf and oceanic waters are dominated by picoplankton-sized unicellular cyanobacteria (*Synechococcus*) and prochlorophytes (*Prochlorococcus*), together with nitrogen-fixing cyanobacterial rafts of *Trichodesmium* and characteristic assemblages of open-ocean dinoflagellates[92, 93, 20, 21].

Mesozooplankton communities also show cross-shelf patterns, with distinct inshore and offshore assemblages[103,115,80]. Inshore and estuarine zooplankton communities, where temperatures can seasonally exceed 30°C, are dominated by small copepods[81]. Most (62%) of the mesozooplankton biomass is comprised of organisms less than 350 micrometres in size, and regional differences in zooplankton community composition are very small, at least within the inshore community[81].

These marked cross-shelf changes in plankton composition are a result of gradients in the physico-chemical properties of water. These gradients are determined by the dynamic balance between terrestrial inputs of nutrients, water movements alongshore, and oceanic exchanges. The cross-shelf extent of terrestrial influence is governed by bathymetry, the limited cross-shelf extension of river plumes, and the magnitude of a northward-flowing, wind-driven coastal current. As a result, nearshore waters are insulated to some degree from mixing with inter-reef waters on the outer shelf[64,73]. A variety of indicators show that the direct effects of runoff from the land are restricted to the nearshore zone 10 to 20 km in width[41,68,104]. Conversely, at the seaward end of the gradient, upwelled intrusions of the Coral Sea thermocline episodically inject nutrient-rich water onto the outer shelf[5,38]. On occasion, large intrusions of Coral Sea water can extend almost the full width of the GBR lagoon[38].

### 6.1.2 The role of plankton in the GBR

Phytoplankton account for approximately half the global primary production, and consequently play a major role in cycling of atmospheric carbon dioxide ($CO_2$). They are also the major primary producers in the GBR ecosystem[37]. Approximately 70 percent of the estimated 2.2 x $10^5$ tonnes of carbon (C) fixed daily by primary producers in the GBR shelf ecosystem originates from phytoplankton production (58 x$10^7$ tonnes C per year) and, of this, two-thirds is fixed by picoplankton[38].

Micro- and mesozooplankton are the basis of food webs supporting oceanic and many coastal fisheries. Plankton and suspended non-living organic particles directly support a wide variety of suspension-feeding organisms and planktivorous fish on coral reefs. In addition, most benthic macroalgae, invertebrates and fish have a planktonic life stage that is dispersed by currents.

Plankton inhabit and dominate (both numerically and by mass) the largest habitat within the GBR, the pelagic ecosystem. Within the GBR, which has an area-weighted average water depth of 36 metres, this ecosystem has a total water volume of over 7200 km$^3$. By contrast, coral reefs comprise about 6 percent of the area within the GBR Marine Park[69].

### *6.1.2.1 Production and energy flow*

GBR waters are characterised by rapid rates of phytoplankton growth, pelagic grazing and remineralisation[40]. *In situ* growth rates for the dominant phytoplankton species range from approximately one to several doublings per day. Fast growth results in a high demand for nutrients and, given the low ambient concentrations of dissolved nitrogen and phosphorus, rapid cycling occurs. Ammonium cycling times range from hours to a few days, and phosphate and nitrate cycling times are typically less than a few days[40]. The cyanobacterium *Trichodesmium* plays an important role in the ecosystem by fixing significant quantities of atmospheric nitrogen. One estimate of new nitrogen fixation suggests that the contribution of *Trichodesmium* is at least of the same order as that entering via riverine discharge[12].

Despite the relatively high rate of primary production, mesozooplankton in GBR waters appear to be food limited[70,77,80,81]. Grazing experiments indicate that essentially all picoplankton biomass production and 62 percent of the nanoplankton production are consumed daily by microzooplankton. Approximately 30 percent of the production by nano- and microphytoplankton is grazed by mesozooplankton[97]. The balance of pelagic production either is respired within the water column, or settles to the ocean floor. Furnas et al.[39] estimated that 25 to 100 percent of particulates in the water column fall to the ocean floor each day, and must therefore be an important driver of benthic ecosystems. Assuming a primary production rate of 0.67 grams C per metre squared per day[40] and copepod production of 8.5 milligrams C per metre squared per day[81], the transfer efficiency between these trophic levels is only 1 percent, supporting the hypothesis that microbial food chains (ie the microbial loop) dominate waters of the GBR.

Some indication of the importance of mesozooplankton in the GBR can be gained by calculating the flux of organic matter through this compartment from both *in situ* production and import of biomass. Based on a rate of copepod production in shallow inshore regions of the GBR of approximately 8.5 milligrams C per metre squared per day[81], we calculate that *in situ* copepod production in the entire GBR is greater than 630,000 tonnes C per year. Though copepods are the most important group numerically, other types of zooplankton that have received less attention are likely to add significantly to pelagic production. For example, appendicularians grow faster than any other multicellular organisms[57] and can be almost as abundant as copepods in GBR waters, although there are no estimates of their production in the region.

There is also likely to be a significant import of oceanic plankton into the GBR from the Coral Sea. Brinkman et al.[15] estimated oceanic inflow into the GBR of 0.58 Sv (1 Sv = 1,000,000 cubic metres per second). Assuming an average biomass of 100 milligrams per cubic metre (wet weight of zooplankton greater than 200 micrometres) in the Coral Sea[70], this would equate to an annual import of 1.83 million tonnes wet weight, equivalent to 110,000 tonnes C.

### *6.1.2.2 Pelagic–benthic linkages*

Plankton are an important food resource for many components of the GBR ecosystem. Soft corals have been shown to graze picoplankton carried onto coral reefs[28], and scleractinian corals are effective zooplankton feeders[105]. Planktivores make up the largest trophic guild of fishes living at shallow depths

on the faces of GBR coral reefs[114], both by weight and by number. Reef-associated planktivorous fish are a diverse group that differ in their degree of dependence on plankton or suspended particulate matter for food, and partition their feeding activity into different reef zones[51]. These fishes remove most of the mesozooplankton from the water prior to it impinging on the reef face. In open waters, megafauna such as manta rays, whale sharks and some species of turtles are also dependent on plankton for food.

Though the contribution of particulate food to reef ecosystems is poorly quantified at larger scales, there have been some attempts to quantify the contribution of plankton and suspended particulate material to individual reefs. Fabricius and Dommisse[27] measured depletion rates of suspended particulate material in tidal channels at the Palm Islands and estimated a carbon removal rate by soft corals of approximately 900 grams C per metre squared per year, similar to estimates made in the Red Sea by Yahel et al.[116]. These studies suggest that soft corals remove an order of magnitude more organic matter from the overlying water than hard coral-dominated reef flats. In turbid coastal waters, some hard corals are able to compensate for low light levels by increasing heterotrophic feeding activity[6]. Holzman et al.[56] showed that actively swimming zooplankton avoid the benthic boundary layer (approximately 1.5 metres thick) of Red Sea coral reefs, below which there is high plankton predation by fishes[84]. Hamner et al.[51] estimated that the flux of zooplankton to 'the wall of mouths' on the face of Davies Reef (central GBR) was 0.5 kilograms per metre per day. At specific locations, the interaction of strong currents and bottom topography may act to greatly amplify the contribution of zooplankton to coral reefs via trophic focusing[43].

An important component of the pelagic environment that is receiving greater recognition as a significant food resource for coral reefs and other habitats is marine snow. Marine snow is the assemblage of largely organic particles or aggregates that are visible to the naked eye (generally greater than 0.5 mm). Marine snow is formed by aggregation of organic material from a variety of sources including polysaccharides from diatoms[65] and discarded appendicular houses[1]. Aggregates are a rich substrate for the growth of micro-organisms, which in turn are concentrated and available to larger-particle consumers such as mesozooplankton, macroplankton and fish. These large particles or aggregates facilitate the settling of organic material onto coral reefs. The extent and importance of this trophic link between pelagic production and the reefs of the GBR ecosystem are yet to be adequately quantified.

### 6.1.3 Critical factors regulating plankton communities

The abundance and growth of planktonic organisms are directly influenced by several climate stressors that will respond to climate change. These include water temperature, ocean chemistry, light, ultraviolet radiation (UVR) and nutrient enrichment. We believe, however, that the direct impact of these climate stressors on plankton species and communities will be overshadowed by the indirect influence of climate change on oceanographic processes that affect the mixing and advection of water masses. We have a limited understanding of how climate change will affect light, nutrient enrichment, mixing and advection of water masses at local and regional scales. Therefore, in assessing these factors, a range of scenarios is considered.

### 6.1.3.1 Temperature

All plankton are poikilothermic and thus are directly influenced by water temperature[26]. More broadly, studies in other regions of the world have shown that plankton growth and development[60,46,66], abundance[95], distribution[9], and timing of blooms[24] are all influenced by temperature. However, these studies were conducted in temperate regions with marked seasonal temperature changes and thus should be applied with some caution to tropical regions.

### 6.1.3.2 Ocean chemistry

Over the last 200 years, oceans have absorbed 50 percent of the anthropogenic $CO_2$ injected into the atmosphere, causing chemical changes that increase the proportion of dissolved $CO_2$, lower pH (approximately 0.1 pH units) and decrease the saturation state of carbonate minerals (calcite, aragonite) in the water[99]. Effects of ocean acidification and increased carbonate dissolution will be greatest for plankton species with calcified (calcium carbonate) shells, plates or scales. These organisms include coccolithophorids, foraminifera, molluscs, echinoderms, and some crustaceans. For these organisms, sea water has to be saturated with carbonate to ensure that, once formed, their calcium carbonate structures do not redissolve. Acidification reduces the carbonate saturation of sea water, making calcification more difficult and dissolving structures already formed.

All phytoplankton obtain dissolved $CO_2$ by passive diffusion, but this can lead to carbon limitation at times of rapid demand. To increase the efficiency of $CO_2$ utilisation, many types of phytoplankton have evolved $CO_2$-concentrating mechanisms to actively transport and accumulate inorganic carbon[44,10]. An increase in dissolved $CO_2$ may well increase the proportion of species that are only capable of passive diffusion of $CO_2$.

Increases in dissolved $CO_2$ can also change the nutritional composition of phytoplankton, such as decreasing the carbon to nitrogen ratio and increasing carbon to phosphorus and nitrogen to phosphorus ratios[11]. Additionally, the proportion of unsaturated fatty acids can decrease, as well as the patterns of macromolecular synthesis. This may have a flow-on effect on growth and reproduction of zooplankton, and increase the production of marine snow, hence affecting nutrient and carbon cycling.

### 6.1.3.3 Light and ultraviolet radiation

Many copepod species are sensitive to changing ambient light levels. Light is the most important cue for zooplankton diel vertical migration and emergence, and has been implicated as a cue in the copepod swarming behaviour that occurs on GBR coral reefs[50]. For example, *Oithona oculata* forms small swarms around coral heads, whereas larger *Acartia australis* swarms form around coral heads and blanket the bottom of reef lagoons[76]. In late summer, *Centropages orsinii* can also form swarms in the deeper parts of reef lagoons. Although the mechanism behind the formation of zooplankton swarms is not well understood, we do know that light is an important determinant of copepod aggregations[18,4].

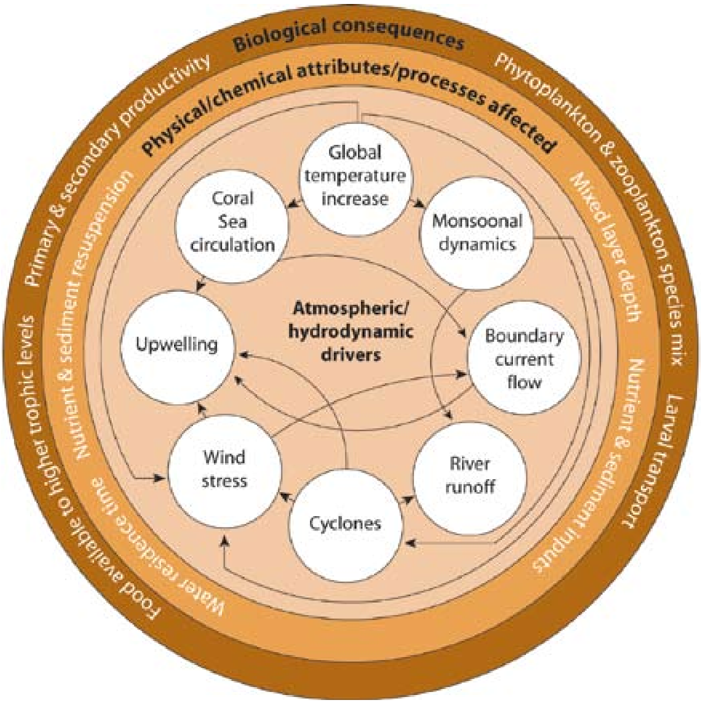
Diel migration patterns in GBR holoplankton communities appear to be weak, though studies to date on vertical migration of GBR zooplankton are equivocal[30,81]. In contrast, emergent zooplankton are a striking feature of the night time plankton within coral reefs[102,2,107]. Even small differences in light, such as occur on moonlit versus non-moonlit nights, can cause changes in the composition of emergent zooplankton assemblages[3].

The highly energetic ultraviolet radiation (UVR) component of sunlight penetrates the surface layers of the ocean and may have detrimental effects on plankton. In the last quarter of the 20th century, there has been an increase in UVR reaching the surface of the earth due to thinning of the protective ozone layer by anthropogenic ozone-depleting substances such as chlorofluorocarbons, halons and hydrochlorofluorocarbons[22]. Since the implementation of the Montreal Protocol in September 1987 to reduce emissions of such substances, stratospheric ozone levels have stabilised. Most climate models show that the ozone layer will recover and thicken throughout the 21st century[22], and presumably UVR will also decline[75], although there remains uncertainty in the timing of the ozone thickening because of the complexity of atmospheric chemical processes[62].

### 6.1.3.4 Nutrient enrichment

Large-scale oceanographic and atmospheric drivers that influence nutrient input and mixing processes include: (i) circulation patterns, (ii) rainfall and the coupled runoff of sediment and nutrients, (iii) frequency and intensity of shelf-break intrusions and topographic upwelling, (iv) frequency and intensity of cyclonic disturbance, (v) wind stress and its effects on sediment resuspension, vertical mixing and coastal current dynamics. These atmospheric and hydrodynamic processes interact in complex ways (Figure 6.1), influencing the physical and chemical attributes of the water column that regulate food web structure, productivity, and dispersal of plankton communities.

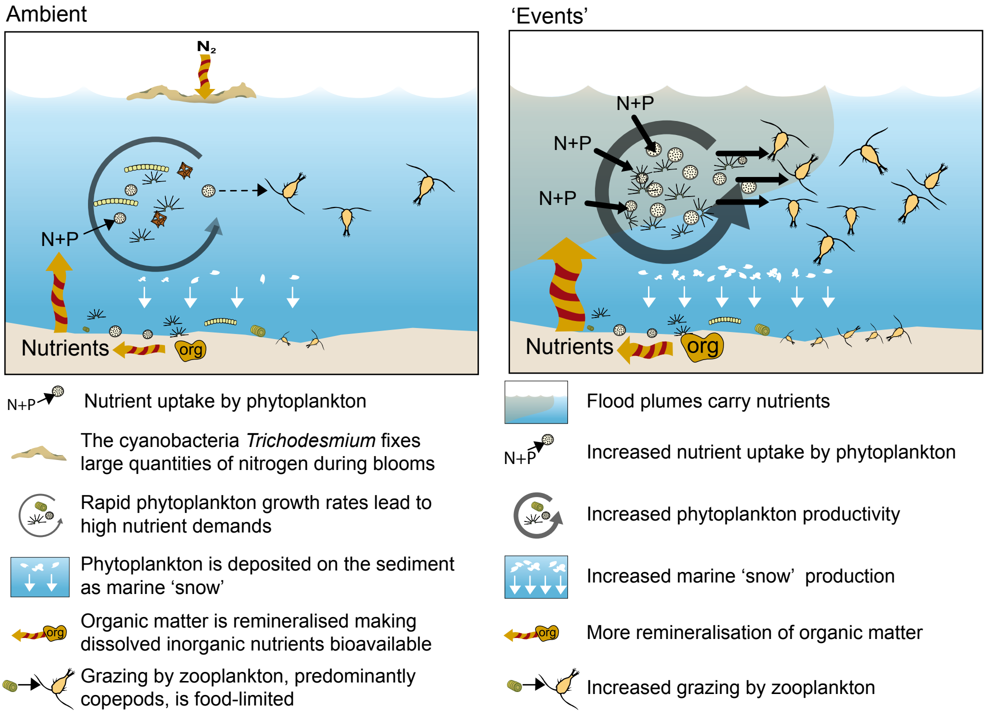
***Figure 6.1*** *Complex interrelationships between atmospheric and hydrodynamic drivers, effects on physical and chemical processes, and biological consequences*



Global warming affects several atmospheric and oceanographic processes including the Coral Sea circulation, monsoonal dynamics, wind stress and cyclones, all of which change the physico-chemical environment of the GBR with impacts on food web structure and function.

Phytoplankton productivity, biomass and community composition in the GBR lagoon are most strongly influenced by event-driven processes affecting the input or availability of nutrients (Figure 6.2). These processes include terrestrial freshwater runoff[33], rainfall[38], sediment resuspension following cyclones[74,112], upwelling from the Coral Sea thermocline[5,38] and lateral exchanges of oligotrophic surface water from the Coral Sea[15]. Nutrient input events occur episodically throughout the year, but they occur most often during the summer wet season. Phytoplankton communities developing after such events are characterised by assemblages of fast-growing diatoms[92,31,32,35]. For example, a large diatom-dominated phytoplankton bloom throughout the central GBR followed Cyclone Winifred in 1986[31]. Liston[70] observed increases in zooplankton biomass, particularly of herbivorous copepods, after Cyclone Charlie in 1989, and McKinnon and Thorrold[80] reported significant increases in copepod biomass and production rates in the Burdekin River flood plume. Climate change factors that influence the frequency, intensity or duration of the wet season and its associated nutrient inputs will therefore have a significant effect on the composition and productivity of phytoplankton communities.

***Figure 6.2*** *Effects of a nutrient enrichment event, using a flood plume example, on plankton abundance, composition and production of marine snow*



In terms of large-scale oceanographic processes, climate-driven changes to the intensity of the South Equatorial Current, which flows westward across the Coral Sea, will directly affect the strength and volume of the southward-flowing East Australian Current (EAC) and the northward-flowing Hiri Current. Changes in the intensity of the EAC, in particular, directly affect the strength of the southward-flowing residual current through the southern half of the GBR. This in turn influences inter-reef mixing and dispersal and water residence times within the lagoon. The strength of the EAC influences the intensity and frequency of shelf-break upwelling along the southern half of the GBR through geostrophic adjustments in the thermocline depth along the continental slope.

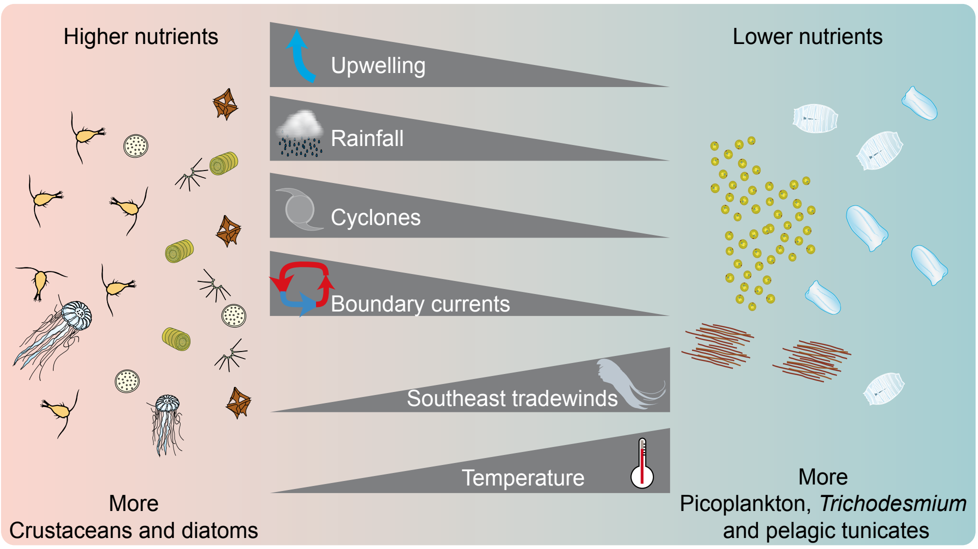
The frequency and size of upwelling events in the central GBR are dependent upon interactions between regional wind stress (strong south-easterly, calm or northerly) and the depth of the Coral Sea thermocline which is in part, determined by the strength of the EAC. Seasonal wind stress patterns are influenced by the dynamics of the northern Australian monsoon and interannual ENSO dynamics. Upwelling is likely to be more frequent when there is a stronger monsoon (more prevalent northerly winds) or during La Niña periods and weaker during stronger SE trade winds. Furnas and Mitchell[35] describe midshelf blooms of cells greater than 10 micrometers in size, mainly diatoms, in water advected sufficiently inshore to have a residence time of about one week. These pulses of production by large phytoplankton cells result in more efficient energy transfer to higher trophic levels and increased secondary production. Wind stress from the south-easterly trade winds is also the primary driver for the northward-flowing coastal current along the entire GBR. This current and the shear zone between it and the southward-flowing residual current are partly responsible for the retention of terrestrial materials near the coastline. Finally, strong winds over the GBR also cause resuspension of bottom sediments in depths less than 20 metres. Resuspension is a source of nutrients to coastal plankton, but also increases turbidity and results in a decrease in photosynthetic depth.

Changes in the intensity and duration of the summer monsoon will influence the quantity of freshwater inputs to the GBR, either directly as rainfall or indirectly as terrestrial runoff. The volume of terrestrial runoff and its source within the GBR catchment, in turn, have a direct effect upon the quantity of sediment and nutrients entering the GBR. During periods of heavy runoff, the inshore plankton community can extend out as far as the midshelf reefs[103]. McKinnon and Thorrold[80] were able to detect an increase in secondary production (as copepod egg production) subsequent to a flood event, and an elevation in zooplankton biomass that lasted two months after the event.

Cyclones produce large regional ($10^3$ to $10^4$ km$^2$) disturbances with enhanced nutrient inputs, mineralisation and plankton production. Liston[70] found that both nutrients and chlorophyll concentrations increased in Bowling Green Bay subsequent to a cyclone. However, the strongest signal was observed in zooplankton abundance and biomass, which showed a fourfold increase two weeks later. Such event-driven pulses in production may have significant implications for food availability for planktivorous fish, larval fish and invertebrate larvae, especially if these events coincide with spawning events.

Our understanding of how plankton communities of the GBR will respond to this complex array of atmospheric and hydrodynamic drivers can be summarised in Figure 6.3. Other factors, including acidification, UVR and cloudiness are considered in section 6.2. We envisage the plankton community as a continuum of states, ranging from those dominated by picoplankton, *Trichodesmium* and gelatinous zooplankton (pelagic tunicates), to those dominated by diatoms and crustacean zooplankton (copepods). Even this is simplistic, as many states may exist at the same time in different parts of the GBR. Local or regional nutrient enrichment is the key determinant of the state of the plankton community; elevated nutrient conditions lead to short and efficient food webs dominated by copepods that are high-quality food resources for planktivorous fish, corals and ultimately piscivorous fish, seabirds and mammals, whereas low nutrient conditions lead to a long and inefficient food web that supports a far lower biomass of higher trophic levels.

***Figure 6.3*** *How physical drivers and stressors regulate plankton community interactions and dynamics*[a]



## 6.2 Vulnerability

Planktonic organisms all have short life cycles: hours to days for phytoplankton, seven to ten days for copepods, and weeks to months for macrozooplankton[52]. In the warm and typically sunny waters of the GBR, the entire phytoplankton community essentially turns over on a daily basis. Dominant copepod species have generation times in the order of a week or two. This means that plankton organisms and communities respond quickly to changes in their physical environment and, as such, are sentinels of environmental change that respond more rapidly than longer-lived animals such as fish, birds and mammals. It also means that the impact of climate change on event-scale processes will be particularly important.

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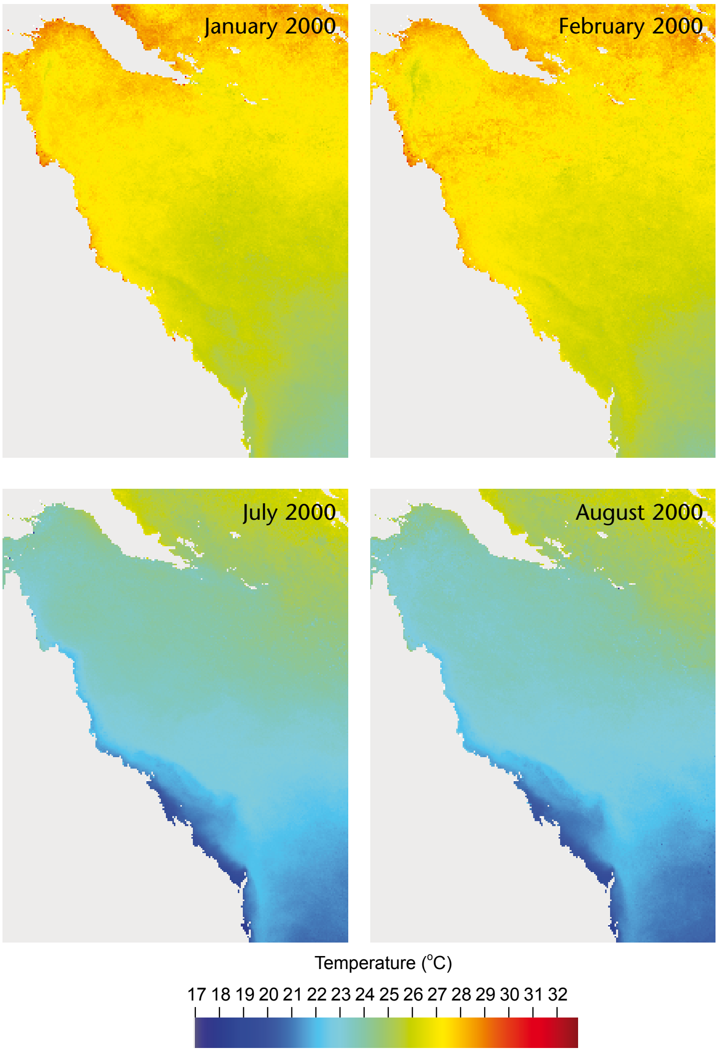
[a] Acidification, UVR and cloudiness are considered in section 6.2.

### 6.2.1 Changes in water temperature

#### *6.2.1.1 Exposure – water temperature*

Exposure of plankton to increased water temperatures is unavoidable. The GBR currently exhibits considerable variation in temperature (Figure 6.4), both seasonally and over its 15 degrees of latitudinal extent from Torres Strait (9° S) to Lady Elliott Island (24° S). Although the water column is generally well mixed, vertical temperature differences can exceed 5°C during intrusion events from the Coral Sea[38]. Consequently, direct effects of small temperature changes on plankton will likely be minimal given the temperature range already encountered within the waters of the GBR.

***Figure 6.4*** *Variation in sea surface temperature on the Great Barrier Reef (Courtesy Mike Mahoney, AIMS)*



### 6.2.1.2 Sensitivity – water temperature

Culture studies[106] indicate that species with tropical and subtropical distributions have growth temperature ranges that encompass the temperature range in the GBR at the present and the range likely in the near future (ie warming by 1 to 2°C), but with optima less than 30°C. In most cases, however, these experiments have been carried out with temperate strains, so potential regional adaptations to warmer temperatures are not apparent. Optimal growth for the dominant picophytoplankton species *Synechococcus* and *Prochlorococcus* in the GBR was found to be between 20 and 30°C[34]. Studies of *Synechococcus* and *Prochlorococcus* in the Atlantic Ocean have shown that *Synechococcus* growth peaked at 28°C, while *Prochlorococcus* peaked at 24°C[83].

Growth rates of copepods are faster at warmer temperatures[60], although this is not always achieved in the GBR because of food limitation. The $Q_{10}$ of copepods is approximately 3 (ie a 10°C change in temperature results in a threefold change in physiological rates such as growth). Small inshore copepods such as *Parvocalanus crassirostris*, *Oithona attenuata* and *O. nana* occur in estuaries where maximum summer water temperatures exceed 30°C[79]. *P. crassirostris* thrives at these temperatures, with growth rates to 1.2 per day at 29°C in the Caribbean[57]. Available evidence indicates that copepod growth and egg-production rates in waters of the GBR exhibit little seasonal variation and are primarily regulated by food availability rather than temperature[70,80,77,81]. However, generation times of the common coastal copepod *Acrocalanus gibber* decrease by 25 percent with a 5°C rise in temperature[77]. In addition, copepod body length typically declines with increasing temperature, though differences in condition (dependent upon food supply) often obscure a causative relationship between weight and temperature[77].

### 6.2.1.3 Impacts – water temperature

As individual plankton species have their own thermal optimum and limits for growth, warming will have differential effects on the growth of individual species. Changes in temperature are more likely to directly affect metabolic processes (growth, respiration) rather than overall community biomass, particularly if plankton communities are resource limited (nutrients, food), and overall productivity may not change greatly. There may also be an enhancement of stratification due to the increase in temperature in the GBR, which will favour picoplankton, *Trichodesmium* and pelagic tunicates. Change in phytoplankton community composition and productivity will have flow-on effects to the productivity of zooplankton grazers.

### 6.2.1.4 Adaptive capacity – water temperature

Most tropical plankton species have relatively broad temperature ranges relative to daily and annual temperature fluctuations in the GBR. While the warmest temperatures encountered in the GBR lagoon and adjacent estuarine waters are above the published optimal growth temperatures for many species, these species can still survive and grow. Our understanding of temperature responses based on laboratory studies is constrained by the fact that individual species often have substantial strain variation. Therefore, there may be undescribed strains with higher thermal optima, improving the ability of individual species to adapt to change[42,13,101]. It is unknown whether individual species in local plankton populations have higher thermal optima than those used in experimental studies, but a changing environment would select for individuals and species better able to grow and survive under changing conditions.

There is some evidence however, that not all species are able to genetically adapt quickly enough to tolerate the projected oceanic warming rate. In such cases, species with preferences for warm water have expanded their ranges towards the poles, and species with cooler-water preferences have retracted to higher latitudes[9]. Despite many plankton species having a fairly catholic distribution throughout the GBR, it is likely that there will be some southward movement of tropical species, with a concomitant range contraction of subtropical species at the northern extent of their range in the southern GBR. For example, the highly venomous box jellyfish (*Chironex fleckeri*) is at the southern limit of its range in North Queensland and may expand its range further south as waters warm.

Warming may also result in earlier periods of peak abundance. This has been observed for many terrestrial groups including the earlier flowering of daffodils and the earlier arrival of migratory birds[90,98]. No work has been done on the timing of maximum plankton abundance in the GBR, but observations from temperate waters may provide some clues despite the much greater seasonality at such high latitudes. In the North Sea, temperature thresholds cue spawning and influence the development of larval stages[24,46,66]. Larvae of echinoderms, lamellibranchs, fish, and decapods are temporary members of the plankton (meroplankton) and their timing is sensitive to temperature[24,46]. Data from the North Atlantic have shown that the timing of peak abundance for these larvae is more than a month earlier now than 50 years ago[24]. If echinoderm larvae in the GBR respond similarly, peak larval abundances of crown-of-thorns starfish could appear earlier in the year. Warming could also lead to the earlier production of meroplanktonic larvae such as medusa stages of box jellyfish (*Chironex fleckeri*).

### *6.2.1.5 Vulnerability and thresholds – water temperature*

Plankton are vulnerable to ocean warming, as they inhabit the GBR waters throughout their life, they are poikilothermic and have short generation times. Worldwide no plankton species are known to have become extinct, but the possibility of extinctions cannot be discounted. Individual plankton species can persist as cryptic populations (below the threshold of detection by sampling methods). The greatest effect of temperature on plankton in the GBR is likely to be on species composition and metabolic fluxes.

## 6.2.2 Changes in ocean chemistry

### *6.2.2.1 Exposure – ocean acidification and increased dissolved $CO_2$*

Plankton cannot escape exposure to changes in ocean chemistry, such as increased dissolved $CO_2$ and ocean acidification.

### *6.2.2.2 Sensitivity – ocean acidification*

Plankton groups with calcium carbonate structures will be sensitive to ocean acidification, though it is possible that physiological stress as a result of acidification may occur in a broader range of organisms. Calcified plankton differ in their susceptibility to acidification depending on whether the crystalline form of their calcium carbonate is calcite or aragonite. Calcite has a higher stability (is less soluble) than aragonite, making it less susceptible to dissolution. Coccolithophores (calcifying phytoplankton), foraminifera (protist plankton), and non-pteropod molluscs produce calcite, the more stable form of calcium carbonate. Coccolithophorids show reduced calcite production and an increased proportion of malformed liths at increased $CO_2$ concentrations[96]. Pteropods are the most sensitive planktonic group because their shell is composed of aragonite, which will be subject to increased dissolution under more acidic conditions[88].

### 6.2.2.3 Impacts – ocean acidification and increased dissolved $CO_2$

The direct effect of ocean acidification on calcifying zooplankton will be to partially dissolve their shells, increasing shell maintenance costs and reducing growth. Foraminifera contribute a significant proportion of the sediments in sandy regions of the GBR. Acidification will deform the calcite scales of coccolithophorids, but this group of phytoplankton occurs only sporadically on the GBR and is found more frequently in the Coral Sea (Furnas, unpublished data), although the coccolithophorid community there is diverse[49].

Pteropods and heteropods are relatively uncommon members of GBR zooplankton assemblages, though the pteropod *Cavolinia longirostris* can form aggregations in summer[100]. *C. longirostris* is likely to be the plankton organism most sensitive to climate-induced change in pH.

Declining pH may also alter the growth rates of photosynthetic organisms. In particular, changes in pH will affect nutrient uptake kinetics, altering rates of growth and photosynthesis. Changes may also occur in phytoplankton cell composition, which could affect their nutritional value for higher trophic levels.

Phytoplankton species lacking carbon-concentrating mechanisms may well increase in dominance under higher concentrations of dissolved $CO_2$. However, the proportion of these species in tropical waters is unknown, but some coccolithophores are able to increase photosynthetic rate in response to elevated $CO_2$.

### 6.2.2.4 Adaptive capacity – ocean acidification

Within the next several centuries, first the aragonite and then the calcite saturation state of GBR waters may decline below levels needed for shell formation and maintenance in calcifying plankton organisms. Orr et al.[88] suggested that pteropods would not be able to adapt quickly enough to live in undersaturated conditions. Undersaturation of aragonite and calcite in sea water is likely to be more acute at higher latitudes and then move toward the equator. Therefore, there is unlikely to be a refuge for these species further south as temperatures warm.

### 6.2.2.5 Vulnerability and thresholds – ocean acidification

Pteropods, with their aragonite shells, are highly vulnerable, while coccolithophorids, foraminifera and some crustaceans, with their calcite shells and liths, are less vulnerable. Pteropods are likely to decline and may eventually disappear in response to ocean acidification on the GBR. No quantitative work on thresholds has been conducted, but experiments on the pteropod *Clio pyrimidata* at 788 parts per million $CO_2$ for 48 hours[88] and the coccolithophores *Emiliania huxleyi* and *Gephyrocapsa oceanica* at 780 to 850 parts per million[96] led to shell and lith deterioration respectively. These experiments were both conducted at $CO_2$ levels approximating those that are likely to exist around the year 2100 under a business-as-usual scenario of greenhouse gas emissions.

## 6.2.3 Changes in light and ultraviolet radiation

### *6.2.3.1 Exposure – light and ultraviolet radiation*

Plankton that inhabit the euphotic zone (greater than 1% of surface light) are sensitive to changes in light and ultraviolet radiation (UVR). The exposure of plankton to light and UVR is dependent upon surface light conditions, dissolved coloured substances and particulate matter in the water column[85].

### *6.2.3.2 Sensitivity – light and ultraviolet radiation*

Changes in light intensity affect phytoplankton growth. Many species of zooplankton will also be sensitive to changes in light, as they exhibit swarming and vertical migration behaviours.

Many neustonic copepods (residing close to the surface) such as the Pontellidae have pigments to reduce damage caused by UVR. Some copepod species on the GBR contain carotenoid pigments with UVR-absorbing properties[7]. Temporary members of the zooplankton that reside close to the sea surface (eg eggs and larvae of fish) can be sensitive to UVR and are likely to receive higher doses.

### *6.2.3.3 Impacts – light and ultraviolet radiation*

Persistent levels of cloud cover reduce light levels and thus primary production, with concomitant declines in secondary production and food for higher trophic levels. In addition, as light is also the cue for both swarming and vertical migration, any changes in the light field will impact these zooplankton behaviours.

UVR impacts the growth, mobility and cellular stoichiometry and the relative dominance of many phytoplanktonic organisms. Tropical regions like the GBR naturally receive high UVR doses. Studies have found that UVR affects nitrogen uptake and thus the growth and productivity of important phytoplankton species[23]. UVR negatively influences several physiological processes and cellular structures of phytoplankton including photosynthesis, cell motility and orientation, algal life span, and DNA machinery[54,55,71]. These effects compromise the ability of phytoplankton to adapt to changing environmental conditions[47,48]. They also result in changes in cellular elemental stoichiometry including increased cellular carbon content, decreased chlorophyll a content, and less frequent cell division resulting in increased cell size[54].

Irradiation of the copepod *Acartia clausi* with high doses of UVR resulted in curtailed adult survival and reduced fecundity[61]. A 20 percent increase in UVR resulted in the death of eight percent of anchovy larvae[59]. UVR can also damage eggs and larvae of copepods, crabs, and fish[25].

UVR can cause changes in community structure because small cells are more prone to deleterious effects of UVR than large cells, and have comparatively high metabolic costs to screen out damaging UVR[91]. Changes in the cellular elemental stoichiometry of phytoplankton caused by UVR often decrease the nutritional value of phytoplankton. Negative effects of such altered food quality can propagate to zooplankton[63]. Further, UVR lowers copepod fecundity, increases naupliar mortality and affects vertical distribution[61,14].

### 6.2.3.4 Adaptive capacity – light and ultraviolet radiation

Some phytoplankton may partially acclimate to or repair UVR damage, although this involves metabolic costs that reduce the energy available for cell growth and division. Mycosporine-like amino acids confer protection against UVR damage in some taxa[11]. Many UVR-tolerant species produce dense surface blooms, some of which are toxic; leading to the possibility that increased UVR may increase the incidence of toxic surface blooms.

### 6.2.3.5 Vulnerability and thresholds – light and ultraviolet radiation

We suggest that the overall vulnerability of plankton to changes in the light and UVR regime is relatively low; moreover, UVR is likely to decline in the longer term. The tropics are naturally high-light and high-UVR environments. At this time, there has been insufficient research to report thresholds of vulnerability for tropical species.

## 6.2.4 Nutrient enrichment

### 6.2.4.1 Exposure

Changing nutrient inputs to the water column of the GBR will affect planktonic species and communities.

### 6.2.4.2 Sensitivity – nutrient enrichment

All phytoplankton species are affected by nutrient enrichment processes to some degree. Diatoms are likely to be particularly responsive to changes in nutrient availability. Zooplankton are not directly affected by nutrient enrichment.

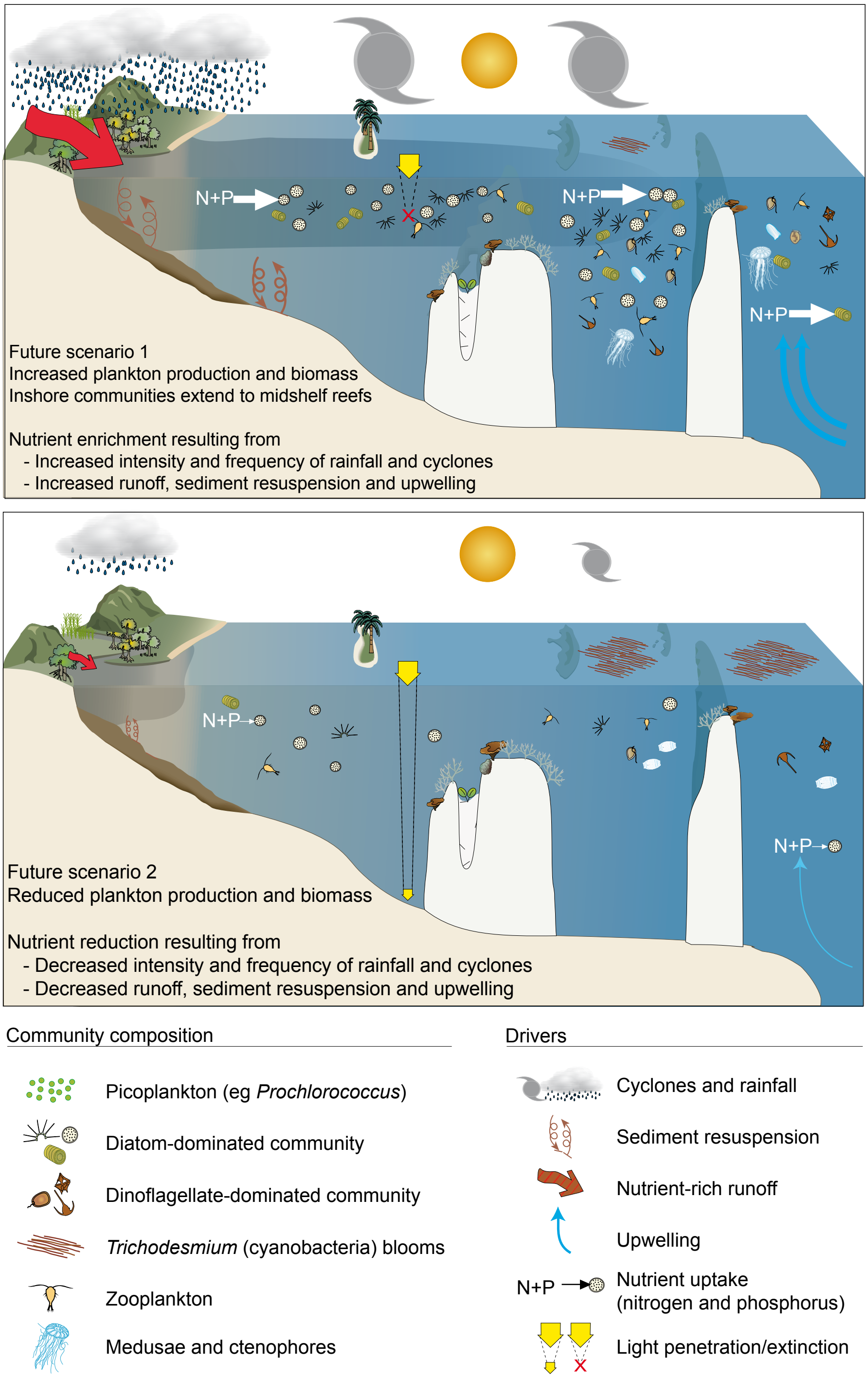
### 6.2.4.3 Impacts – nutrient enrichment

Changes in oceanographic and weather processes, which affect nutrient inputs to the GBR ecosystem (eg upwelling, runoff and resuspension), will have direct influences on plankton abundance, community structure, and production and thereby affect higher trophic levels (Figure 6.3).

There are likely to be changes in the abundance of phytoplankton, with lower nutrient conditions leading to less plankton, and enhanced nutrient conditions resulting in greater plankton abundance (Figure 6.5). The cyanobacterium *Trichodesmium* is either toxic or of poor nutritional quality to most copepods – only some pelagic harpacticoids graze *Trichodesmium*[86,87]. Phytoplankton and zooplankton community structure will also change, with picoplankton and the nitrogen-fixing cyanobacterium *Trichodesmium* likely to be more important if nutrient input processes decline (Figure 6.5). As a result, under low nutrient conditions, small non-crustacean zooplankton and gelatinous filter-feeding groups (salps, doliolids, appendicularia) will be more prominent, while enhanced nutrient conditions may favour larger crustacean zooplankton. Under nutrient enrichment, diatoms are likely to increase, leading to more crustacean zooplankton and carnivorous medusae and ctenophores.

Oceanographic processes, which affect residual current strengths on the GBR shelf, will also affect the longshore mixing and dispersal of plankton organisms or life stages and residence times within the GBR system. Climate-driven changes in the relative balance between wind stress and the southward residual current in the southern half of the GBR will influence the cross-shelf extent of coastal plankton assemblages.

***Figure 6.5*** *Future scenarios under two different nutrient enrichment regimes*



#### *6.2.4.4 Adaptive capacity – nutrient enrichment*

The plankton community will adjust to changes in nutrient inputs and availability by changing its composition. The relative abundance of Picophytoplankton, *Trichodesmium* and gelatinous zooplankton is likely to increase under a low nutrient regime, while diatoms and large zooplankton are likely to be more important under a high nutrient regime.

#### *6.2.4.5 Vulnerability and thresholds – nutrient enrichment*

The plankton community is affected by changes in the degree of nutrient enrichment. Whether this constitutes vulnerability is open to debate. The concept of a threshold may not apply in this situation. We consider there is a continuum between the two end-member states (Figure 6.5).

## 6.3 Linkages with other ecosystem components

Altered phytoplankton and zooplankton abundance, composition, productivity and timing of occurrence will have a cascading effect on higher trophic levels of the GBR. Any decline (or increase) in overall abundance, growth and trophic efficiency of phytoplankton and zooplankton communities is likely to lead to the decline (or increase) in higher trophic levels. Larvae of almost all fishes feed on copepod nauplii at first feeding[58], and therefore variations in the timing and extent of copepod reproduction could influence patterns of recruitment of fishes and economically important invertebrates, especially those with a long larval life, such as crayfish. This will be discussed more fully in Kingsford and Welch (see chapter 18). Synchronous and infrequent events in plankton (eg coral spawning) may be affected by changes in the magnitude and timing of primary and secondary productivity, and changes in the predators present. Changes in runoff regime may affect the life cycles of stingers and productivity of the coastal zone where they feed.

Pteropods contribute to the diet of carnivorous zooplankton, myctophids and other zooplanktivorous fish, and a reduction in pteropods may have ramifications higher up the pelagic food web. Over long timescales, the calcite-producing foraminifera are likely to be negatively impacted by reduced pH.

### 6.3.1 Constraints to adaptation

Smaller plankton species have shorter life cycles and hence presumably greater scope for genetic recombination. They are therefore more likely to adapt physiologically than larger plankton. However, predation rather than physiological stress is the principal source of mortality in plankton organisms. Local oceanographic factors determine the movement of water across natural climatic gradients much larger than those that we expect from climate change alone. Plankton organisms are therefore more likely to be carried into and out of the GBR ecosystem before any significant adaptation could occur. If adaptation does occur, it will most likely be through regional-scale selection of genotypes more closely attuned to warmer temperatures and shorter generation times.

### 6.3.2 Interactions between stressors

At large scales, atmospheric and hydrodynamic variables interact to produce a complex temporal and spatial pattern of nutrient enrichment (Figure 6.1). At local scales, the predictive value of temperature as a stressor is often overridden by concurrent resource limitation. In the GBR ecosystem, phytoplankton growth rates are more dependent upon nutrient availability than temperature (Furnas unpublished data). In estuarine ecosystems, which are less likely to be nutrient limited, models based on biomass, photic depth and incident irradiance outperform models based on temperature alone[16]. Similarly for zooplankton, growth rates are related more to food availability than temperature.

Another interaction between stressors is between UVR and the depth of the mixed layer. A decrease in the depth of the mixed surface layer, coupled with an increase in turbulence, increases exposure of phytoplankton to UVR and the chance of algal cells receiving harmful doses[63,53]. UVR can also interact with nutrient availability, as enhanced UVR can increase the availability of essential macronutrients via increased photochemical dissolution of organics, thus enhancing phytoplankton growth[94,89,113].

### 6.3.3 Threats to resilience

The plankton community as a whole is resilient to changes in climate-related stressors such as large-scale nutrient enrichment, temperature, acidification, UVR and winds. Plankton groups that are not favoured by the prevailing conditions will be restricted to certain favourable environments in space and time, and the plankton community is able to reorganise to maintain key functions and processes. The continuum between different states summarised in Figure 6.3 has different trophic efficiencies; the ability of communities dominated by picoplankton and pelagic tunicates to provide food for higher trophic levels is limited in comparison with communities dominated by diatom and large zooplankton.

## 6.4 Summary and recommendations

### 6.4.1 Major vulnerabilities to climate change

Apart from some estuarine copepods, there are no known endemic species of holoplankton in the GBR ecosystem. There is a low probability of extinction risk; no plankton species worldwide are considered to have become extinct, although many plankton species are cryptic, difficult to identify, or undescribed, and almost none have any regular assessment of their status. Therefore, as individual plankton taxa may not be particularly vulnerable (the pteropod *Cavolinia* is an exception) and there is also insufficient information for any individual taxa to assess potential vulnerabilities, we have taken a functional group approach. Table 6.3 summarises findings on the vulnerability of plankton functional groups from section 6.2. The column order of the stressors reflects our judgment of the perceived vulnerability of plankton and ecosystem consequences to each stressor, namely nutrient enrichment, temperature, ocean chemistry, and light and UVR.

We consider that the most likely changes in plankton communities will be a consequence of alterations in atmospheric and oceanographic variables that drive nutrient enrichment processes, and that changes in other stressors will probably have a smaller secondary impact on plankton and the ecosystems they support.

***Table 6.3*** *Summary of vulnerability of plankton to climate change. The column order of the stressors reflects our judgment of the perceived vulnerability of plankton to each stressor, with nutrient enrichment being the most important and light/UVR the least.*

| | *Stressors* | | | |
|---|---|---|---|---|
| | **Nutrient enrichment (upwelling, winds, rainfall, cyclones)** | **Temperature** | **Ocean chemistry** | **Light and UVR** |
| Exposure | • Phytoplankton spend their entire life cycle in GBR waters so will be exposed to and directly responsive to changes in nutrient enrichment processes. | • Plankton spend their entire life cycle in GBR waters so will be exposed to increased regional temperature. | • Plankton spend their entire life cycle in GBR waters so will be exposed to acidification as a result of increased dissolved $CO_2$. | • Plankton spend their entire life cycle in near-surface GBR waters so will be exposed to changes in light and UVR. |
| Sensitivity | • All phytoplankton species would be responsive to some degree, but diatoms are particularly responsive to changes in nutrient conditions.<br>• Increase in dissolved organic matter (DOM) from runoff may locally favour dinoflagellates and heterotrophic protists over diatoms. | • Species-specific effects, with some having wide and others narrow temperature tolerances.<br>• Short generation times make plankton particularly sensitive.<br>• Substantial response of rate processes such as growth.<br>• Copepod growth in GBR more related to phytoplankton abundance than temperature. | • Those with aragonite shells such as pteropods will be most sensitive and adversely affected.<br>• Those with calcite shells such as coccolithophores, foraminiferans, some molluscs & crustacean larvae will be affected, but to a lesser degree.<br>• Other plankton groups not affected directly | • Photosynthesising organisms (phytoplankton) will be directly affected by light availability.<br>• Zooplankton that exhibit swarming and diel vertical migration behaviours will be sensitive.<br>• Species without photoprotective devices and living in or near surface layers will be most sensitive to UVR. |

***Table 6.3*** *(continued)*

| | *Stressors* | | | |
|---|---|---|---|---|
| | **Nutrient enrichment (upwelling, winds, rainfall, cyclones)** | **Temperature** | **Ocean chemistry** | **Light and UVR** |
| Impacts | • Change in phytoplankton community structure (see Fig. 6.2), with dominance of picoplankton and *Trichodesmium* if nutrient availability declines, and more diatoms if nutrient availability increases<br>• Change in primary productivity (see Fig. 6.2), with lower production rates if nutrients decline, and higher rates if nutrients increase.<br>• Zooplankton will respond indirectly, via their trophic linkage with phytoplankton.<br>• Change in zooplankton community structure (see Fig. 6.2), with increased dominance of small crustacean zooplankton if nutrients decline, and more medusae and ctenophores if nutrients increase.<br>• Change in secondary productivity (see Fig. 6.2), with lower production rates if nutrients decline, and higher rates if nutrients increase.<br>• Declines/increases in primary and secondary production will lead to depressed/enhanced marine snow sedimentation. | • Change in primary and secondary production.<br>• Change in community structure (see Fig. 6.2), with more picoplankton, *Trichodesmium* and small zooplankton.<br>• Most copepod species decrease in body size with warming.<br>• Phenology of spawning and production of larvae | • Dissolution of shells<br>• Disappearance/ reduction of species | • Change in primary production, with a decline if cloud cover increases (light decreases).<br>• Change in zooplankton swarming patterns, with more swarming if clouds were to decline (light increases)<br>• Change in zooplankton emergence, with amphipods, cumaceans, mysids, and ostracods emerging more frequently if cloud cover was to decline (light increases).<br>• Change in community structure, particularly size.<br>• Cell mutation<br>• Increased cell death<br>• UVR can affect nutrient availability and uptake in phytoplankton. |

**Table 6.3** *(continued)*

| | | *Stressors* | | |
|---|---|---|---|---|
| | **Nutrient enrichment (upwelling, winds, rainfall, cyclones)** | **Temperature** | **Ocean chemistry** | **Light and UVR** |
| Adaptive capacity | • Nature of change in community structure is adaptive.<br>• Restriction of plankton groups to certain favourable environments in space and time | • Change to strains of a species that may be better adapted<br>• Change in distribution<br>• Change in timing of life history events | • None known, but physiological buffering possible | • Changed pigment content in phytoplankton cells<br>• Change in vertical structure of phytoplankton<br>• Zooplankton exposed to more intense UVR can augment their pigment content. |
| Vulnerability and thresholds | • Plankton community is not highly vulnerable, with a continuous response rather than a threshold due to the complexity of response and number of plankton species. | • Plankton community directly affected, with a continuum response rather than a threshold due to the complexity of response and number of plankton species. | • Pteropods highly vulnerable; other molluscs, coccoliths, foraminifera and some crustaceans less vulnerable; and other plankton not directly vulnerable.<br>• No threshold work | • Phytoplankton productivity is highly vulnerable to changes in light availability, as are some zooplankton, but thresholds unknown. |

**Table 6.3** *(continued)*

| | *Stressors* | | | |
|---|---|---|---|---|
| | **Nutrient enrichment (upwelling, winds, rainfall, cyclones)** | **Temperature** | **Ocean chemistry** | **Light and UVR** |
| Linkages and Interactions | • Climate impacts on plankton cascading to higher trophic levels<br>• Reduced trophic efficiency within the plankton if picoplankton dominate<br>• Decreased food quality and quantity for higher trophic levels if picoplankton dominate<br>• Decline in abundance of higher trophic levels if picoplankton dominate<br>• Changes in food availability for benthic detritivores if picoplankton dominate | • Possible consequences for higher trophic levels<br>• Reduced trophic efficiency within the plankton<br>• Decreased food quality and quantity for higher trophic levels<br>• Decline in abundance of higher trophic levels | • Consequences for higher trophic levels unknown but may be relatively minor<br>• Over long times scales, decreased amount of sedimentation of foraminifera shells<br>• Decreased rate of sedimentation (reduced density of shells that carry attached organic matter to depth) | • Possible consequences for higher trophic levels<br>• Change in primary production most critical, with effects cascading to higher trophic levels<br>• Consequences for higher trophic levels unknown but may be relatively minor |

### 6.4.2 Potential management responses

As most of the climate change impacts on plankton are driven by large-scale oceanographic, weather and climate processes, few local management responses are possible. Further, because of the enhanced levels of $CO_2$ in the atmosphere and rates of fossil fuel burning, the process of ocean acidification is irreversible over the next several centuries. The only practical way to ameliorate these effects is to reduce $CO_2$ emissions to the atmosphere. This requires a global solution.

Ocean acidification will have direct consequences on some plankton groups. Broad-scale addition of chemicals to the ocean to re-equilibrate the pH is not practical, and it will take thousands of years for ocean chemistry to return to a condition similar to that of pre-industrial times[99].

Perhaps the only action likely to succeed at the regional scale would be the reduction of terrestrial runoff of sediment, nutrients and chemical pollutants through widespread changes in land use practices within the GBR catchment. This would help maintain the structure and functioning of existing plankton communities in the GBR lagoon. Efforts to make such changes are now under way through the Reef Water Quality Protection Plan.

### 6.4.3 Further research

The lack of information on the state of GBR plankton communities currently hinders policymakers from being able to fully address the impacts of climate change on the GBR. This is a consequence of the lack of long-term (multi-decadal) plankton datasets in the region. The longest dataset for a crude system variable such as plankton biomass (eg chlorophyll a) commenced in 1989, covering coastal waters between Cape Tribulation and Cape Grafton. During this period, there has been a slight, non-linear decrease of 30 percent in chlorophyll, although there is no clear evidence that this change is climate driven. Much of the impact of climate change in plankton systems elsewhere has not been apparent from such bulk indices but from species-specific changes in distribution, timing of life-cycle events or in changes of rate processes.

As part of an overall environmental monitoring program for the GBR, consideration should be given to the inclusion of one or more plankton monitoring sites (perhaps based at island research stations) to track long-term changes in plankton biomass and community structure, particularly for those few forms (eg pteropods) that are at particular risk from ocean acidification.

Species-specific sampling of plankton over larger areas is more difficult. Ocean colour satellites provide information on bulk indices such as surface chlorophyll, but no species-specific information on phytoplankton or zooplankton. One possibility is to use the continuous plankton recorder, a robust yet cost-effective device for capturing phyto- and zooplankton that is towed behind commercial vessels. A route is beginning in 2007 from Brisbane to Fiji, but none is currently planned closer to the GBR.

Most of the climate-influenced changes in GBR plankton communities will result from changes in atmospheric and oceanographic variables that drive transport, mixing and nutrient input processes.

Fortunately, many of the critical environmental variables underpinning these processes such as water temperature, cloud cover, solar radiation, UVR and wind stress are already routinely collected as part of the research and monitoring of the GBR (eg Australian Institute of Marine Science weather stations and Transports of the East Australian Current System moorings) and need to be continued.

In terms of critical research foci in the future, we can highlight two areas. First, we have insufficient knowledge of the role of marine snow as a linkage between pelagic and coral reef ecosystems. Studies so far have provided tantalising glimpses into this linkage but much remains to be discovered. Second, in this review we have identified that nutrient input processes are critical to understanding future climate change impacts on the GBR. The big unknown is the direction of these processes – whether inputs are going to increase or decrease and whether the spatial and temporal pattern of inputs will change. Hydrodynamic and geochemical modelling efforts focused on the intensity of the boundary currents bordering the GBR and in the Coral Sea (East Australian Current and Hiri Current) as well as upwelling dynamics and riverine runoff are pivotal to answering these questions. Only with nutrient–phytoplankton–zooplankton models embedded within these hydrodynamic models will we be able to understand and forecast the response of the plankton community and thus higher trophic levels.

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## Part II: Species and species groups

# Chapter 7

# Vulnerability of macroalgae of the Great Barrier Reef to climate change

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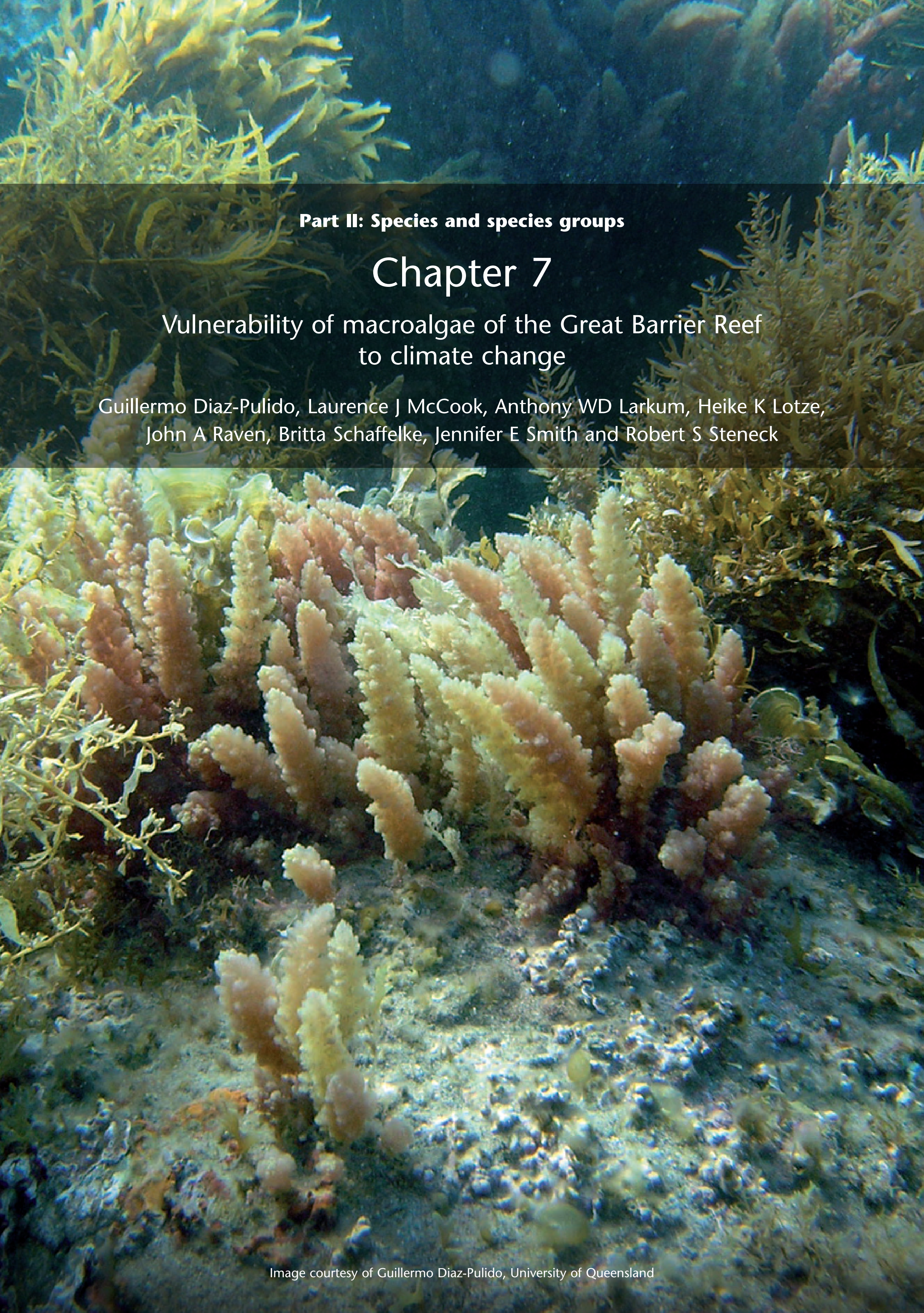


Image courtesy of Guillermo Diaz-Pulido, University of Queensland

## 7.1 Introduction

### 7.1.1 Macroalgae of the Great Barrier Reef

### *Definition and scope*

Macroalgae is a collective term used for seaweeds and other benthic marine algae that are generally visible to the naked eye. Larger macroalgae are also referred to as seaweeds. The macroalgae of the Great Barrier Reef (GBR) are a very diverse and complex assemblage of species and forms. They occupy a wide variety of habitats, including shallow and deep coral reefs, deep inter-reef areas, sandy bottoms, seagrass beds, mangroves roots, and rocky intertidal zones.

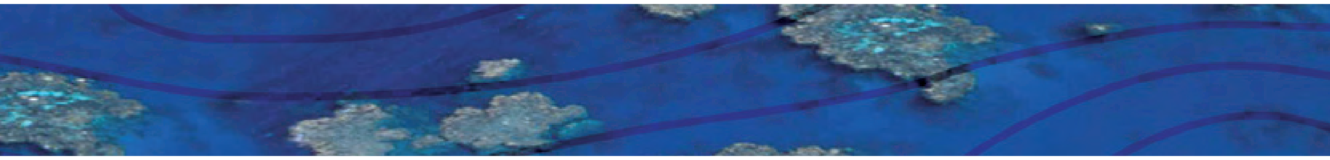
Macroalgae broadly comprise species from three different phyla: Rhodophyta (red algae), Heterokontophyta (predominantly Phaeophyceae, the brown algae), and Chlorophyta (the green algae) (Table 7.1). Macroalgae are clearly distinguished from microalgae, which require a microscope to be observed (eg phytoplankton, benthic and pelagic diatoms, free-living dinoflagellates, cyanobacteria (blue-green algae) and the symbiotic zooxanthellae that live within coral tissue). In some cases, benthic microalgae, such as some cyanobacteria and Chrysophyta, form large colonies that resemble thalli of macroalgae[172,158]. Such colony-forming cyanobacteria are often common components of turf algal assemblages and, in this context, will be included in this chapter.

### *Taxonomic diversity*

GBR macroalgae are an important component of Australia's marine plant biodiversity. The Australian Marine Algal Name Index lists 629 species (including varieties) recorded for the GBR[41], accounting for nearly 32 percent of the total number of algal species recorded for the continent (although the compilation for the GBR is based on very limited collections). In addition to being relatively diverse at the species level, GBR macroalgae have complex and diverse evolutionary histories[6,200], including more than 40 orders belonging to at least five phyla (Table 7.1) and two kingdoms (Prokaryota and Eukaryota). In contrast, for example, hard corals include only one to two orders.

***Table 7.1*** *Systematic diversity of coral reef benthic macroalgae in comparison with hard corals*

| Taxonomic group | Orders | Phyla |
|---|---|---|
| Benthic macroalgae | ~40 | 5<br>• Rhodophyta (red algae)<br>• Heterokontophyta (class Phaeophyceae: brown algae; Class Bacillariophyceae: diatoms)<br>• Chlorophyta (green algae)<br>• Chrysophyta (golden algae, especially the predominantly benthic class Pelagophyceae)<br>• Cyanophyta (blue-green algae, especially colonial cyanobacteria) |
| Hard corals | ~2<br>Scleractinia<br>Milleporina | 1<br>Cnidaria |



Assessing the vulnerability of benthic macroalgae is further complicated by the fact that the taxon 'algae' is an unnatural (and, some suggest, outdated) grouping that encompasses several distinct and diverse evolutionary lines. Adl et al.[3] suggest that 'algae' remains a useful functional term, denoting photosynthetic protists and their multicellular derivatives which are not embryophytes (higher plants), as well as cyanobacteria. However, they also show that 'algae', like 'protists', is not a formal taxon (and therefore should not be capitalised), nor a single, homogeneous group.

### *Functional form group diversity*

Macroalgae are not only more diverse than most other groups in coral reef habitats, they are also more complex, in functional morphology and ecological roles. In tropical habitats, macroalgae range from small, structurally simple, filamentous turfs, a few millimetres high, or heavily calcified crustose forms, to large leathery macrophytes, such as *Sargassum*, up to several metres tall (Table 7.2). Given this diversity, different macroalgae should be assumed to respond in qualitatively different ways to the stressors associated with climate change: they cannot be considered as a uniform group.

In addition to taxonomic groups, macroalgae can be considered in terms of functional groupings, based on plant attributes and ecological characteristics (such as the form of the plant, size, toughness, photosynthetic ability and growth, grazing resistance, etc)[117,118,191]. The three main categories are: i) algal turfs, ii) upright macroalgae (fleshy and calcified), and iii) crustose calcareous algae. Each category includes several 'functional groups' (Table 7.2). This approach is considered more useful by ecologists, because it reflects both physiological traits and the role of algae, whereas ecological roles are not well correlated with taxonomic groupings.

***Table 7.2*** *Categories and functional groups of benthic algae present in the Great Barrier Reef, as used in this vulnerability assessment*

| **Algal categories** | | **Functional groups** | | **Examples of common genera in the GBR** |
|---|---|---|---|---|
| Algal turfs (less than 10 mm height) | | Microalgae | | *Lyngbya, Chrysocystis* |
| | | Filamentous | | *Cladophora, Polysiphonia* |
| | | Juvenile stages of macroalgae | | |
| 'Upright' macroalgae (greater than 10 mm height) | Fleshy (ie non-calcareous) | Foliose | Membranous | *Ulva, Anadyomene* |
| | | | Globose | *Ventricaria, Dictyosphaeria* |
| | | | Corticated | *Dictyota, Lobophora* |
| | | Terete Corticated | | *Laurencia, Acanthophora* |
| | | Leathery | | *Sargassum, Turbinaria* |
| | Calcareous | Calcareous articulated | | *Halimeda, Amphiroa* |
| Crustose algae | | Calcareous Crustose | | *Porolithon, Peyssonnelia* |
| | | Non-calcareous Crustose | | *Ralfsia, Cutleria* |

### Distributions and seasonal dynamics

GBR algal communities are highly variable, showing latitudinal, cross-shelf and within-reef variation in composition and abundance[139,134]. Cross-shelf differences in seaweed composition are especially pronounced. In contrast to inshore reefs, offshore reefs usually have low abundance of fleshy macroalgae, but high cover of crustose calcareous algae (CCA)[a] and turf assemblages. Species of fleshy macroalgal genera such as the green algae *Caulerpa*, *Chlorodesmis*, and *Halimeda*, and the red algae *Laurencia*, *Spyridia*, *Galaxaura* and *Liagora* are often present on offshore reefs, but in low abundance[160]. Brown algae are generally low in abundance, with the most common genera including *Padina*, *Dictyota*, *Turbinaria* and *Lobophora*[131,133,67]. CCA are abundant and diverse on offshore reefs and can contribute to reef formation[177,39,157,66] (Steneck and McCook unpublished data). Abundant taxa on offshore reefs include *Porolithon, Neogoniolithon, Paragoniolithon,* and *Lithophyllum* species (Steneck unpublished data).

Inshore reefs usually have abundant and conspicuous macroalgal assemblages. In particular, the often extensive reef flats are dominated by dense and highly productive beds, up to four metres tall, of large, fleshy brown seaweeds, predominantly *Sargassum*, as well as *Hormophysa*, *Turbinaria* and *Cystoseira* (all from the order Fucales, the rockweeds) and a variety of larger red algae[139,149,127,203,170,133].

Seaweeds are also abundant in some deep-water, inter-reef areas of the northern part of the GBR. Large mounds formed from deposits of the green calcareous alga *Halimeda* are estimated to cover up to 2000 km$^2$ in this region and may be up to 20 metres high[142,126,61]. These *Halimeda* meadows occur principally in northern sections of the GBR, at depths between 20 and 40 metres, but they are also found in the central and southern sections, where they have been found at depths down to 96 metres[61]. The GBR apparently contains the most extensive beds of actively calcifying *Halimeda* in the world, although the real extent of such meadows is unknown. The extensive deep meadows of *Halimeda* in the northern section of the GBR (at depths between 30 and 45 metres) appear to be sustained by nutrients injected by tidal jets and localised upwelling events[59,212].

In addition to this spatial variability, many GBR macroalgae are highly seasonal in their occurrence, growth and reproduction[149]. Large seaweeds such as *Sargassum* are strongly seasonal, with peaks in biomass and reproduction during the summer and lowest biomass during the winter[127,203,170,55]. A large proportion of the GBR benthic algal species, especially red algae, grow most actively during the Australian autumn (March to May), winter dry season (June to August), and spring[149]. Extensive but ephemeral blooms of smaller, fleshy brown macroalgae, such as *Chnoospora* and *Hydroclathrus*, have been observed on shallow reef flats predominantly during winter and early spring[170,32].

### The challenge: assessing the vulnerability of a group with diverse ecological roles

In this paper, we consider the vulnerability of benthic macroalgae to climate change in terms of the vulnerability of natural assemblages and distributions, rather than simply the overall abundance of the entire group. That is, if a turf algal assemblage undergoes a marked shift in species composition, but remains dominated by turf algae, that assemblage is nonetheless vulnerable.

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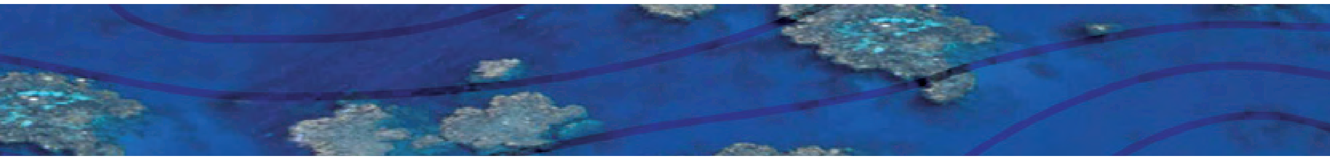
[a] As used in this chapter, the term crustose calcareous algae (CCA) includes all calcified algal crusts, including members of both the families Corallinaceae (ie non-geniculate coralline algae, called crustose coralline algae) and Peyssonneliaceae.



Also critical to this assessment is recognition that different macroalgae have different ecological functions, contributing both to the maintenance of reef health, and to the degradation of reefs (see section 7.1.2). Disturbances or stresses such as climate change may lead to an overall increase in total amount of macroalgae, but this may be detrimental to the ecosystem as a whole, and does not mean that macroalgae as a group are not vulnerable. Some taxa, groups or assemblages of algae may thrive, but others may decline markedly, in response to direct impacts, or indirectly if, for example, out-competed by more successful algae. The outcome will be algal assemblages, and ecosystems, that are markedly different in terms of taxonomic composition, function, and the relative and overall abundance of different taxa. In this scenario, the macroalgal flora of the GBR is clearly vulnerable.

Further, the different algal groups outlined above (Tables 7.1 and 7.2) are likely to respond to climate change stressors in distinct and different ways. However, while this is true for both taxonomic and functional groupings, assessing the vulnerability of taxonomic groups is unlikely to be relevant in terms of ecological outcomes, because the broader taxonomic groups (ie above order) are not well correlated with ecological roles and functions.

For these reasons, we have assessed the vulnerability of GBR macroalgae based on the ecologically derived functional categories identified in Table 7.2, as the approach and level of detail most useful to environmental managers or researchers. While there will clearly still be considerable variation within these categories, more detailed treatment is not warranted by the available information, and is beyond the scope of the present chapter.

### 7.1.2 Ecological roles of macroalgae in the Great Barrier Reef

Macroalgae have critical and complex roles on coral reefs of the GBR, including making significant contributions to primary production, nitrogen fixation, construction and cementation of reef framework, facilitation of coral settlement, and creation of habitats for other reef species. Macroalgal colonisation and abundance have also been recognised as causes – or, more importantly, consequences – of coral reef degradation.

#### *7.1.2.1 Contribution to primary production and carbon storage*

A large proportion of the primary production (the formation of organic matter by plants through photosynthesis) on a coral reef is contributed by benthic algae, particularly by algal turfs[74]. Available research from the GBR indicates that primary production by fleshy macroalgae and crustose algae is also important[170,38]. Planktonic microalgae and algal symbionts of scleractinian corals contribute to reef productivity to a lesser degree[1]. The organic matter produced enters the reef food web by several pathways. Many algae are directly consumed by herbivorous fishes, crabs, sea urchins and mesograzers, while dissolved organic carbon released by the algae into the water enters the microbial food web[29]. Some organic matter is exported as detritus by currents and tides to adjacent habitats such as seagrass meadows, mangroves and the deeper, inter-reef sea floor. There is no published information on primary production of benthic algae in GBR habitats other than coral reefs.

Reefs dominated by fleshy macroalgae, such as inshore reefs and reef flats, may play important roles as short-term sinks for atmospheric carbon dioxide ($CO_2$)[73,1]. However, the seasonal and disturbance-driven dynamics of algal abundance and taxonomic composition in the GBR are likely to lead to distinct fluctuations in the metabolic performance (primary production and respiration[15] and therefore in the amount of carbon being stored).

### *7.1.2.2 Nitrogen fixation and nutrient retention*

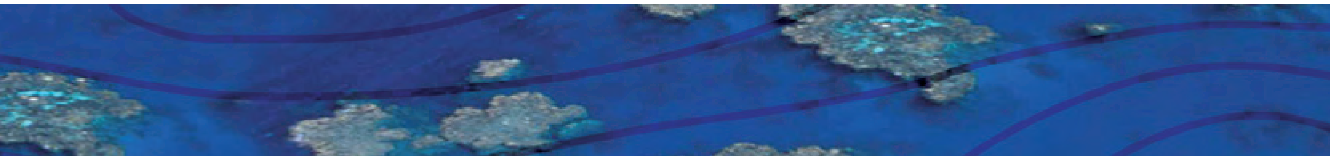
Filamentous blue-green algae living in algal turf communities and on sandy bottoms fix significant amounts of atmospheric nitrogen to sustain their growth independent of dissolved nutrients[99,85]. Due to the rapid growth rates of blue-green algae and intense grazing on turf communities, the organic nitrogen fixed in algal tissue rapidly enters the food web and becomes available for other primary producers[83]. Studies on the GBR have found high rates of nitrogen fixation, particularly on substrates exposed to fish grazing[207,208,108].

### *7.1.2.3 Reef construction and habitat formation*

Many macroalgae make important contributions to the construction of reef framework by depositing calcium carbonate ($CaCO_3$). Crustose calcareous algae (eg *Porolithon* and *Peyssonnelia*) are significant framework builders and framework 'cementers' on coral reefs[114,37]. CCA bind adjacent substrata and provide a calcified tissue barrier against erosion[114]. This process may be particularly important on reef crests on the GBR, where CCA may be the dominant benthic organisms, potentially contributing to reef cementation[42,177,39]. However, the contribution of coralline algae to reef cementation in the GBR (as opposed to cementation that is microbially mediated lithification) has not been quantified, although deposition of calcium carbonate may be high[37]. Geological formations of small CCA concretions (rhodoliths) have been shown to occur over wide areas in shallow and deep continental shelf waters in other parts of the world[13,165,68] and this is likely to be true for Australia and the GBR[68,30]. CCA are important in areas at depths between 80 and 120 metres, at the edge of the continental platform in the southern GBR, where they form large frameworks, several meters high[45].

Upright calcareous algae, such as *Halimeda, Udotea, Amphiroa* and *Galaxaura,* make important contributions to the production of marine sediments[88,60,44]. The white sand of beaches and reef lagoons is largely composed of eroded calcium carbonate skeletons of these algae, as well as foraminiferans and corals. These sediments are important to reef accretion, filling spaces in the reef matrix or structure. Calcium carbonate is deposited as aragonite, calcite and high-magnesium calcite in the algal tissues[114]. Calcification may be an adaptation that inhibits grazing (defensive mechanis)[192,184,185,186,187], resists wave damage, and provides mechanical support and protection from ultraviolet (UV) radiation[114,18].

In habitats such as *Sargassum* and *Halimeda* beds, the macroalgae also provide the three-dimensional structure that defines the habitat ('habitat formers'), in the same way that trees create a forest. Many other organisms find shelter or food within the physical environment created by these algae, and some macroalgal beds may serve as important juvenile or nursery habitats for reef fish and invertebrates (eg Beck et al.[20]).



### *7.1.2.4 Facilitation of coral settlement*

Crustose calcareous algae of the order Corallinales are suggested to induce settlement of coral larvae in the GBR[87]. Recent experimental studies have suggested that the crustose coralline alga *Titanoderma prototypum* is one of the most preferred substrates for coral settlement, with larval settlement rates 15 times higher than on other CCA[81]. The implications of this process at the ecosystem level remain to be explored.

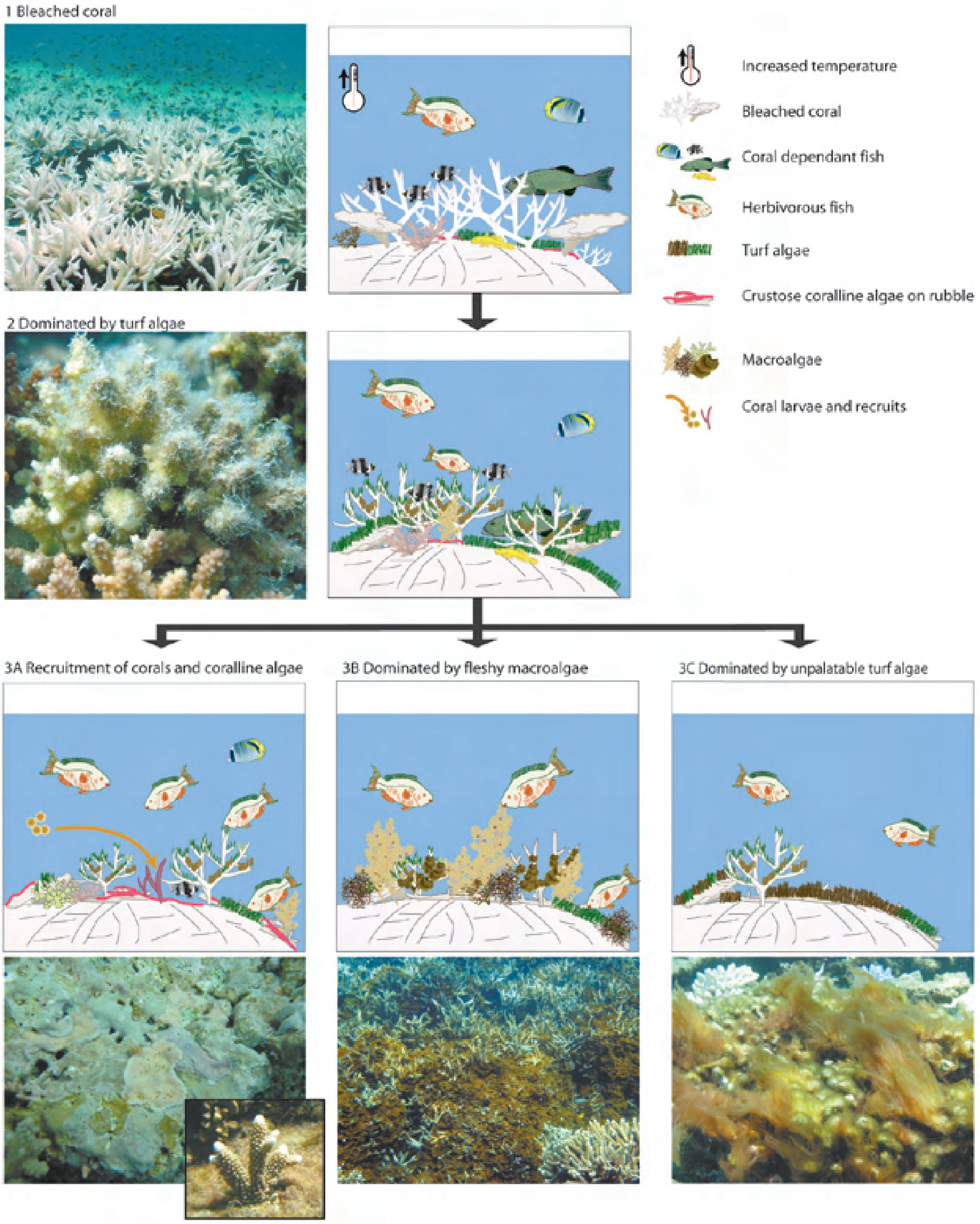
### *7.1.2.5 Reef degradation*

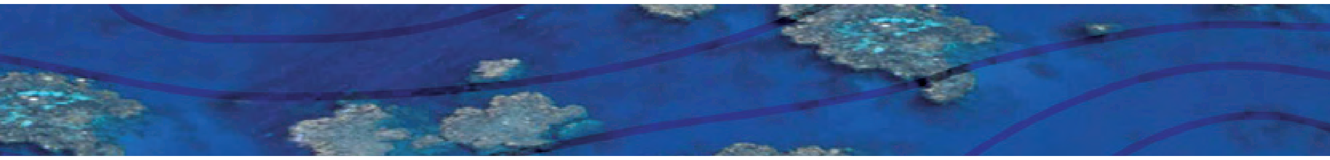
Macroalgae also play critical roles in reef degradation, particularly in ecological phase shifts or gradual transitions, where abundant reef-building corals are replaced by abundant fleshy macroalgae[58,91,132,103,136]. Reductions in herbivory due to overfishing and increases in nutrient inputs have been shown to cause increases in fleshy macroalgal abundance, leading to coral overgrowth by algae and, ultimately, reef degradation[188,132,193,130]. Many disturbances, such as coral bleaching, crown-of-thorns starfish outbreaks, extreme low tides, outbreaks of coral diseases and storm damage (specifically tropical cyclones) often lead directly to coral mortality. The dead coral skeletons are then rapidly colonised by diverse algal communities[148,96,52,78]. A reef community dominated by abundant, high-biomass algal turfs or larger, fleshy macroalgae may lead to overgrowth, smothering and/or shading of corals, the exclusion of coral recruitment, and increases in pathogens, resulting in an alternate stable state, with decreased ecological, economic and aesthetic value[91,194,135,140,181]. A macroalgal-dominated state may be very persistent, especially if the initial stressors that led to coral mortality are still present, and either do not adversely affect the new macroalgal community or have positive feedback effects.

## 7.1.3 Critical factors for survival of macroalgae

The distribution and abundance of macroalgae on coral reefs are determined by the resources they require (ie light, carbon dioxide, mineral nutrients, substrate), the effects of environmental factors (eg temperature, salinity, water movement), individual rates of recruitment, mortality and dispersal, and biological interactions such as competition and herbivory. All these aspects and their interactions are of particular importance under climate change scenarios since they are all likely to be altered (Figure 7.1). For instance, sea temperatures govern global biogeographic distributions of seaweeds and therefore any temperature change is expected to affect distribution ranges and seasonality of reef algae[199,2,176]. Increased resources such as carbon dioxide ($CO_2$) and nutrients may enhance growth rates but the accumulation of biomass will largely depend on interactions with herbivores[132]. In this chapter we consider the impacts of changes in environmental conditions and resources including: i) ocean circulation, ii) seawater temperature, iii) ocean chemistry (sea surface $CO_2$ and the consequent increase in bicarbonate), iv) light and UV radiation, v) sea level rise, vi) tropical storms, vii) rainfall and river flood plumes, and viii) substrate availability.

***Figure 7.1*** *General model of the impacts of global climate change on macroalgae of the Great Barrier Reef and likely outcomes*





# 7.2 Vulnerability of algal turfs, fleshy and crustose calcareous macroalgae to climate change

## 7.2.1 Changes in ocean circulation

### *7.2.1.1 Exposure – ocean circulation*

Perhaps one of the least studied aspects of global climate change, there is only limited information about how ocean circulation might change under global climate scenarios (Steinberg chapter 3). Algal turfs, upright macroalgae and CCA are likely to be considerably exposed to changes in ocean circulation, such as changes in water movement, temperature and quality (eg upwelling or dispersion of flood plumes). For example, a strengthening of the Hiri Current may depress the thermocline, suppressing the ability of cooler deep waters to access the continental shelf (see Steinberg chapter 3) with potential impacts on macroalgal productivity. Cai et al.[33] predict a strengthening of the Eastern Australian Current, but the extent to which this will affect the GBR is not clear.

### *7.2.1.2 Sensitivity – ocean circulation*

Algal dispersal is dependent on ocean currents, and algal distributions and ecological functions (eg productivity, nitrogen fixation) are sensitive to changes in water temperature and water quality (see section 7.1.2.3). There is potential for shifts in species composition, and these changes may be sudden or abrupt, depending on the nature of the circulation changes.

Upright algae, especially of the order Fucales (eg *Sargassum*), are less homogeneous in distribution[133] than turfs or CCA, and hence may be more sensitive to changes in dispersal by water movements. For example, *Sargassum* spp. distributions are restricted to inshore reefs and therefore changes in ocean circulation could affect populations of these algae.

Distributions of CCA depend on water flow, temperature, water quality and dispersal and are therefore sensitive to variation in such factors and processes[113,190,95,2].

### *7.2.1.3 Impacts – ocean circulation*

Impacts of altered ocean circulation on turf algae and most upright macroalgae include potential changes in propagule dispersal and consequent changes in distribution patterns, including range expansions and the potential for species introductions. However, baseline descriptions of GBR algal flora are limited, especially for turfs. Thus, impacts of changing ocean circulation are essentially impossible to assess.

Shifts in temperature and water quality are likely to result in altered distribution patterns (range extensions or contractions) and species composition of algal turfs[175], and consequent changes in ecological functions such as productivity and nitrogen fixation. Increases in seawater temperature, associated with changes in ocean circulation, have been suggested to be causing range contractions of some species of macroalgae along the New South Wales coast[137].

The distribution of beds of *Halimeda* (an upright calcified macroalga) in the northern GBR is known to be a consequence of specific oceanographic conditions (tidal jets), which may be dramatically altered by changes in oceanography (Steinberg chapter 3). However, these are deep-water beds fed by deep ocean currents, potentially diminishing the impacts of decreases in carbonate saturation of surface ocean waters, relevant for shallow sites.

Changes in ocean circulation may cause shifts in habitat suitability for CCA, with consequent changes in distributions, and species composition within habitats. This may have potential flow-on impacts on reef accretion and coral recolonisation after disturbances such as bleaching.

#### *7.2.1.4 Adaptive capacity – ocean circulation*

As groups, algal turfs, upright macroalgae and CCA are likely to adapt (ie adjust, sensu IPCC, see glossary of terms) through shifts in relative abundance of functional groups and shifts in species composition and function. However, such shifts, particularly of turfs and upright macroalgae, are likely to have serious, negative impacts on the adaptive capacity of reefs as they may inhibit the growth of other benthic organisms, particularly after disturbance.

#### *7.2.1.5 Vulnerability and thresholds – ocean circulation*

Baseline descriptions of turf and upright macroalgae flora of the GBR are limited, uncertainties about projected changes in ocean circulation are high, and the consequences of specific changes are not clear. Assessing the vulnerability of algae to changing ocean circulation, therefore, is difficult, but vulnerability is estimated to be low to moderate for algal turfs and CCA, and moderate for upright macroalgae.

### 7.2.2 Changes in water temperature

#### *7.2.2.1 Exposure – water temperature*

Climate change models for the GBR indicate that average annual sea surface temperatures on the GBR are projected to continue to warm over the coming century and could be between 1 and 3°C warmer than present temperatures by 2100[b,93] (Lough chapter 2). Projections also show that extremes in sea surface temperature will shift towards warmer extremes and a reduction in the frequency of cold extremes (Lough chapter 2). Algal turfs, upright macroalgae and CCA from shallow and deep reef zones, from both inshore and offshore reefs, will be exposed to changes in sea surface temperature. Intertidal and shallow-water species of all three groups will experience higher exposure during emersion, and there is potential for interaction with increased desiccation stress.

#### *7.2.2.2 Sensitivity – water temperature*

Although there is no information about temperature tolerances of tropical turf algae or CCA species, studies of subtropical algae suggest tolerances are relatively wide. Temperature tolerances of tropical macroalgal species from elsewhere (non-GBR) indicate a wide range for survival of 8 to 35°C for subtidal species and –2 to 35°C for intertidal species, but many are unable to survive permanently at 35°C (or even 33°C[23,145]. Pakker et al.[145]) also found that intertidal species are generally more tolerant to high temperatures than are subtidal taxa. In the more-severe climate scenarios, projected sea surface temperatures will exceed optima or thresholds for photosynthesis, growth and reproduction.

#### *7.2.2.3 Impacts – water temperature*

Potential impacts of increased sea surface temperature on algal turf, upright macroalgae and CCA species include increased metabolism, increased production[19], and changes in seasonality, growth and

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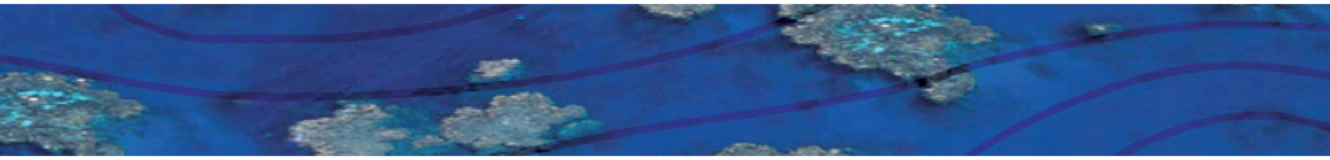
[b] Current monthly average temperatures in coastal GBR: approximately 20 to 29°C, with extremes approximately 18 to 34°C (Australian Institute of Marine Science).



reproduction[31]. Given the diversity of forms and species, potential for widespread direct mortality of turf algae is likely to be low but changes in composition of assemblages are likely.

Seasonal growth and reproduction of temperate upright algae is controlled by temperature and/or day length[124,125], and several studies indicate that this also applies to tropical macroalgae[51,9,10]. While seasonality has been observed in many GBR algae[149,127,160], there is no specific information available on the environmental triggers that may be involved. Without this knowledge, we can only suggest that temperature-controlled life cycles may become unsynchronised under climate change, with potentially catastrophic effects for individual species or food webs (see Sommer et al.[182] for an example from temperate plankton).

The potential for widespread direct mortality of upright macroalgae is low, due to assumed wide temperature tolerances[145]. For calcified upright algae, there may be increased calcification[114,5]. Community changes due to shifts in relative abundance of turf algae and upright macroalgae, and range expansions, are also likely to occur[31,175].

For CCA, there is potential for a slight increase in calcification[c] but this may be greatly offset by the projected increase in ocean $CO_2$ and lower carbonate saturation state. Warmer temperatures may have significant indirect impacts on CCAs. For example, high temperatures favour microbial growth, which may increase the incidence of CCA diseases, such as the Coralline Lethal Orange Disease (CLOD)[116], or the *Peyssonnelia* Yellow Band Disease (PYBD)[50]. Both diseases have been observed more commonly during the warmer months, although the nature and impact of such diseases in the GBR are not known[50].

Changes in sea temperature may increase the potential for a new suite of introduced macroalgal species to establish in GBR habitats (especially ports and other disturbed environments that receive introduced species from human activities such as shipping) because the changed environmental conditions could match their physiological tolerances[174].

### 7.2.2.4 Adaptive capacity – water temperature

There is limited information available on the adaptive capacity of algal turfs, upright macroalgae and CCA to cope with increased sea surface temperatures. However, it is likely to be high for all three groups, due to their wide temperature tolerances and the short generation times of algae.

### 7.2.2.5 Vulnerability and thresholds – water temperature

The vulnerability of algal turfs as a complex is likely to be low but variable, due to the high diversity of turf species and the wide range of temperature tolerances[145]. For example, taxa such as *Ulva* (*Enteromorpha*) and *Cladophora* are eurythermal with large distributional ranges and are likely to be less vulnerable than species with more restricted distributions, such as many turfing red algae (see Price and Scott[151]). The vulnerability of upright macroalgae and CCA is likely to be low to moderate, given their expected high adaptive capacity, and wide temperature tolerances. The effects of higher temperatures on temperature-controlled algal life cycles are not understood.

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[c] Temperate CCA show variable responses to rising temperature[95,100]; information for tropical CCA is very limited[100].

The abundance of fleshy macroalgae and CCA has been negatively correlated with sea surface temperature on reefs of the Red Sea and the Caribbean, while algal turfs are positively correlated with temperature[51, 11]. This may suggest a strong competitive advantage for turfing assemblages under increased temperatures scenarios. However, this pattern requires testing in the GBR.

## 7.2.3 Changes in ocean chemistry

### *7.2.3.1 Exposure – ocean acidification*

Changes to ocean chemistry will increase bicarbonate ions ($HCO_3^-$) with a consequent decrease in pH and carbonate concentration. With continued emissions of $CO_2$, oceanic pH is projected to decrease by about 0.4 to 0.5 units by 2100 (a change from 8.2 to 7.8; Lough chapter 2). Although all benthic macroalgae will be exposed, on reefs from shallow to deep, changes in pH, $CO_2$ and calcium carbonate saturation state will be particularly significant for crustose and upright calcareous macroalgae[163]. There is also potential for changes in the availability of nutrients under reduced pH[163,102].

### *7.2.3.2 Sensitivity – ocean acidification*

The sensitivity of all algal groups is expected to be complex, due to interactions between the effects of pH and $CO_2$ enhancement of photosynthesis. Although there are no data specific to the GBR, a doubling of $CO_2$ produced an increase in growth of 52 percent in a temperate red algae[d,104] and up to 130 percent in other species[e,71]. However, calcified algae are particularly sensitive to ocean acidification. For example, in the GBR, a decrease in pH from 8 to 7.5 reduced calcification dramatically for the alga *Halimeda tuna*[28]. Reduction of pH may also decrease calcification of *Amphiroa foliacea* from the GBR[27f]. Decreases in carbonate saturation state will also inhibit calcification for upright macroalgae and CCA. CCA are the algal group most likely to be affected by ocean acidification, as they are highly sensitive to reductions of saturation state. Minor changes in pH (from 8.1 to 7.8) reduced calcification by as much as 21 percent for a coral reef community that included CCA[g110].

### *7.2.3.3 Impacts – ocean acidification*

Impacts of changes in ocean chemistry will vary between functional form groups. Increased ocean $CO_2$ concentration may enhance rates of photosynthesis and growth (particularly for species with no mechanisms for concentrating carbon), although such increases may be limited by the availability of nutrients[h] and by possible direct effects of acidification on photosynthesis. However, if nutrient availability increases, due to higher terrestrial inputs (see section 7.2.7), there is a possibility of synergistic increases in growth of turf algae (due to increased $C0_2$ and nutrients), further disturbing

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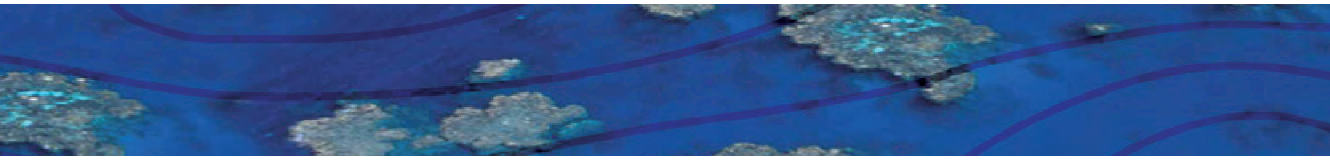
[d] Data for the temperate intertidal fleshy red macroalga *Lomentaria articulata* showed nonlinear response[104].

[e] Data for two species of the red fleshy alga *Gracilaria* from Japan[71].

[f] One of the few experiments that have used macroalgae from the GBR[27]. Effects of acidification in *Amphiroa* seem to be smaller than the effects on *Halimeda tuna*.

[g] Leclerq et al.[110] manipulated $CO_2$ in a coral reef community that included the CCA *Neogoniolithon* spp. and *Hydrolithon* and predicted a reduction of 21 percent in calcification by 2100 (when pH is expected to be 0.4 to 0.5 units lower than at present).

[h] Some studies have shown carbon limitation for planktonic microalgae[163] and temperate fleshy macroalgae[104,154], but there are few specific examples demonstrating carbon limitation of growth of turf algae or fleshy macroalgae from coral reefs[63], including the GBR[109].



the balance between corals and turf algae. Changes in ocean chemistry may alter the availability of nutrients, and temperature increases tend to increase stratification and reduce mixing with nutrient-enriched waters[163]. The overall outcome for turf algae is difficult to predict. Increased ocean $CO_2$ may also increase carbon uptake by turf algae, with a resultant increase in the release of dissolved organic carbon, as has been demonstrated for some microalgae[156].

For fleshy upright macroalgae, impacts of increased $CO_2$ are likely to be similar to those for algal turfs, including enhanced rates of photosynthesis and growth, and increased carbon storage[28,71]. Such increases may be regulated in part by water flow and nutrient availability[63]. There is potential for shifts from carbon-saturated to presently carbon-limited species. Intertidal species are likely to respond less to increased $CO_2$, as they are generally carbon saturated[19].

Ocean acidification reduces calcification of seaweeds such as *Halimeda*[28,47], *Amphiroa*[i,27,105] and *Corallina pilulifera*[70]. Increased $CO_2$ may enhance photosynthesis in such upright, calcified algae, but these effects will be offset against those of decreased calcification as a result of decreased carbonate saturation state; again, the overall outcome is difficult to predict. Acidification may also increase the susceptibility of algae to grazing and erosion, and may lead to a reduction in sand production, significant loss of habitat (eg *Halimeda* banks), and shifts from calcifying to non-calcifying algae[19,101,163,102].

The impacts of increased $CO_2$ on CCA may include not only reduced calcification, but may ultimately include dissolution of calcified skeletons[163,143,102]. Coralline algae calcify with high-magnesium calcite, which is metabolically more costly than aragonite, the form used by *Halimeda* and most other tropical calcified organisms including corals[114]. CCA are sensitive to water temperature and carbonate saturation state as a prime regulator of their growth rate. Recent models suggest a reduction in calcification of 21 percent for a coral reef community (including two species of CCA) by 2100 (when pH is expected to be 0.4 to 0.5 units lower than present[110]). It is worth emphasising that these predictions should be interpreted cautiously, as they are based on very few studies, which have included mainly temperate CCA species[105], and there are no published studies of the effects of acidification for tropical CCA. It is also clear, on the basis of studies of the natural abundance of boron isotopes and the pH of sea water in coral reefs, that there have been pre-industrial to modern interdecadal variations in reef-water pH[146,102]. Further, there are potentially complex interactions between calcification, rising temperature and increasing nutrients, and there is strong evidence (in articulated calcareous algae and corals) that calcification rates are enhanced by photosynthesis, with a mean light-to-dark ratio of about three[75,102].

Increased $CO_2$ may enhance rates of photosynthesis in CCA, as in turfs and upright macroalgae, although increases may be limited by the availability of nutrients and water flow. Net photosynthesis of epilithic algal communities dominated by the crustose calcareous alga *Hydrolithon* (*Porolithon*) *onkodes* was negatively affected by high pressure of $CO_2$[195]. Recruitment of CCA may also be reduced with elevated $CO_2$[4]. Weaker crusts may be more susceptible to grazing, erosion or diseases. These impacts may generate shifts from calcifying crusts to non-calcifying algae, with potential impacts on reef cementation and stability. Loss of CCA may reduce settlement cues for coral larvae, in turn causing a serious reduction in the overall resilience of reef ecosystems.

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[i] Langdon et al.[105] found a 24 to 42 percent decrease in calcification for the predicted change in $CO_2$ between 1880 and 2065 in coral reef mesocosms dominated by upright calcified algae *Amphiroa* spp.

CCA may play a role in cementing reef structures together. Thus, a negative effect on CCA of increased surface water carbon dioxide, and attendant decreased carbonate and pH, is likely to have a negative impact on reef stability. However, the effects that will occur are difficult to forecast without more knowledge.

### *7.2.3.4 Adaptive capacity – ocean acidification*

There is no information on the potential for adaptation of algal turfs, upright macroalgae or CCA to ocean acidification. The adaptive capacity of CCA in particular is critical to reef structures, but is likely to be low, given that calcification is purely a physico-chemically mediated process. Calcified algae can alter their physical and chemical environment for calcification in confined spaces (within the cell wall and intercellular spaces). However, significant adaptation would also require the capacity to influence dissolution of pre-existing parts of the skeleton that abut directly with the surrounding medium. There may be some potential for adaptation by CCA and calcified upright algae by secreting less soluble skeletons (eg lower content of magnesium calcite in calcitic skeletons) as found in the articulated calcareous alga *Amphiroa* (Corallinales) from the Caribbean[183]. Coralline algae (order Corallinales) radiated to nearly modern levels of diversity during the Eocene[185] when the world was much warmer and had higher $CO_2$ than at present[179,138], so adaptation may be possible but in ways we do not yet understand[163]. Crustose algae as a group are likely to persist in the GBR, but at significantly reduced abundances, and with ecologically significant shifts in species composition, distribution and function. Given their apparent importance to coral recruitment, such changes are likely to significantly reduce the adaptive capacity of the ecosystem as a whole.

### *7.2.3.5 Vulnerability and thresholds – ocean acidification*

Overall, the vulnerability of algal turfs and uncalcified upright macroalgae to ocean acidification is low to moderate, depending on the balance between enhanced production, and the effects of decreased pH on growth, nutrient availability and water mixing. Vulnerability of calcareous upright and crustose algae is high, with potential for habitat loss and a reduction in the production of calcareous sand.

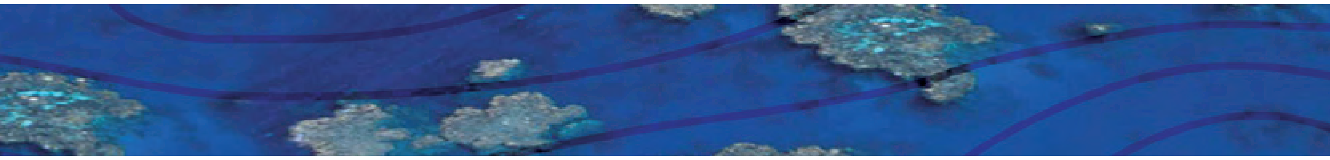
## 7.2.4 Changes in light and ultraviolet radiation

### *7.2.4.1 Exposure – light and ultraviolet radiation*

Ultraviolet (UV) radiation is likely to continue to increase, due to the effects of ozone depletion (Lough chapter 2), and UV levels are already high in tropical regions[201]. Although no significant increasing trends have been observed in the GBR to date, UV penetration is highly dependent on water clarity, suggesting that GBR inshore algae will be less exposed to UV radiation than algae further offshore, and algae in intertidal and shallow-water habitats more than deeper algal assemblages. UVB radiation is more harmful to marine organisms than UVA.

### *7.2.4.2 Sensitivity – light and ultraviolet radiation*

Intertidal and shallow-water algal turf and CCA species appear generally less sensitive than deeper species, apparently reflecting adaptation to high light/light UVB levels, through the accumulation of UVB-screening compounds[108]. Upright macroalgae with thick thalli (plant body) are less sensitive to UV radiation than those with thin thalli, a pattern which applies to differences between species, individuals (old versus young) and thallus parts[62,123,76]. Macroalgal embryos and early life history stages are more sensitive than juveniles and adults[86]. Experimental data for temperate algae have shown that even small doses and short exposure times (eg two hours) of UV radiation will



often reduce photosynthesis, growth and reproduction of turf algae, upright macroalgae and CCA[123, 4,90,162,206]. However, there are no published data for GBR algae.

### *7.2.4.3 Impacts – light and ultraviolet radiation*

There are few experimental studies documenting impacts of UV radiation on tropical algal turfs, upright macroalgae or CCA; most relevant studies are from temperate and polar regions. However, the effects of UV radiation are likely to be comparable. The most common impacts include direct damage to the photosynthetic apparatus[19,72], DNA[69,198], reproductive tissues[19], and reduction of nutrient uptake[57]. There are documented cases of changes in algal secondary metabolites that may consequently alter herbivore consumption[43], with important implications for algal dynamics and interactions. All these effects may lead to community changes, due to shifts in relative abundance[201,46,123], but the potential for widespread direct mortality seems low. Tropical algae are likely to have higher UV tolerances than temperate macroalgae because they have evolved in a naturally high UV environment.

### *7.2.4.4 Adaptive capacity – light and ultraviolet radiation*

Available evidence suggests some potential for algal turf and upright macroalgae species to adapt to high levels of UV radiation, but there is limited information available for CCA. Higher exposure leads to higher levels of UV-absorbing compounds in turf and upright macroalgae (carotenoids, mycosporine-like amino acids)[16]. Higher UV exposure may also cause shifts in assemblage composition to species with a high capacity to produce UV absorbing compounds, or to species that have a broader complement of such compounds[16]. Red macroalgae appear to have higher levels of UV-absorbing compounds than green and brown macroalgae, potentially giving red algae greater adaptive capacity[17]. The presence of phlorotannins in some brown algae may provide some protection against UV radiation[86]. Adaptive capacity apparently increases during succession, apparently because spores are more susceptible than sporophytes to UV damage[j]. Some calcareous upright algae, such as the temperate calcareous alga *Corallina officinalis*, have the potential to adapt to high levels of UV radiation[77] because calcium carbonate acts as a broadband reflector[112,18] and may confer some tolerance in CCA.

### *7.2.4.5 Vulnerability and thresholds – light and ultraviolet radiation*

The vulnerability of algal turfs and upright macroalgae as a whole is moderate since there is potential for adaptation to increased UV radiation and the impacts are likely to be restricted to shallow-water assemblages. The vulnerability of CCA as a group is likely to be low to moderate.

## 7.2.5 Sea level rise

### *7.2.5.1 Exposure – sea level rise*

Sea level rise due to thermal expansion of the oceans and the melting of glaciers and ice sheets is occurring at a rate of one to two millimetres per year. By 2100, the global sea level is projected to be 310 ± 30 mm higher than in 1990 (Lough chapter 2). Inundation of land due to sea level rise will increase available substrate for colonisation by macroalgae in shallow coastal habitats. On the other hand, subtidal areas, especially on platform reefs, may exceed depth limits for survival of certain species, especially for shallow-water algal turfs, upright macroalgae and CCA.

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[j] Experiments with coral reef macroalgae and diatoms[166,167].

### 7.2.5.2 Sensitivity – sea level rise

Intertidal species of algal turfs, upright macroalgae and CCA are likely to expand in area in response to sea level rise due to colonisation of newly available substrate. Within all three algal groups, different taxa will have very different colonisation and dispersal potentials, resulting in highly variable responses to the increase in available substrate with sea level rise.

### 7.2.5.3 Impacts – sea level rise

The potential impacts of sea level rise on algal turfs, macroalgae and CCA include increased colonisation and abundance of turf algae in shallow habitats, and shifts in the placement of the intertidal zone and associated species[79]. Reduced light levels at deeper depths may shift the distribution of deeper-water species. Some reef species, such as reef-crest CCA, may lose habitat due to 'drowning' of reefs.

### 7.2.5.4 Adaptive capacity – sea level rise

Under the assumed scenario of a sea level rise that is slow relative to the life spans of most algal turfs, upright macroalgae and CCA, rapid colonisation and growth rates are likely to confer high adaptive capacities, assuming light levels and substrate availability are suitable.

### 7.2.5.5 Vulnerability and thresholds – sea level rise

Vulnerability of algal turfs, upright macroalgae and CCA to rise in sea level is low. High rates of colonisation, growth and reproduction will, together with high biodiversity of turf species, reduce the vulnerability of all macroalgal groups to sea level rise.

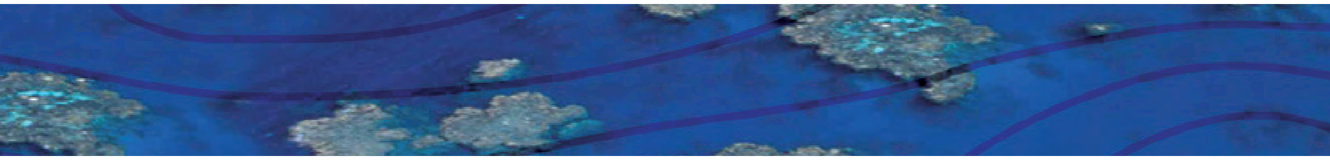
## 7.2.6 Physical disturbance – tropical storms

### 7.2.6.1 Exposure – tropical storms

The intensity of tropical cyclones is projected to increase in the future, although there is uncertainty as to whether their frequency will increase (Lough chapter 2). The exposure of algal turfs, upright macroalgae and CCA to tropical cyclones is related to their proximity to storms, both spatially and temporally. Shallow-water algal turfs, macroalgae and CCA assemblages are more likely to be exposed to the physical forces and wave energy of cyclones than deeper assemblages. Since conditions suitable for cyclone development in the GBR occur from November through May, algal assemblages growing during this season will be more exposed. For example, the main growth and reproductive season of canopy-forming Fucales (eg *Sargassum*) is during this period, making them highly exposed. Algal turfs, upright macroalgae and CCA are also likely to be exposed to increased nutrients, resuspension of sediments and increased water flow associated with cyclones (section 7.2.7), but the most important effect is likely to result from increased substrate due to damage to corals (section 7.2.8).

### 7.2.6.2 Sensitivity – tropical storms

The small size of turfing and CCA species, their creeping or crustose habits, well-developed anchoring systems (holdfasts), and rapid growth rates and reproduction will presumably minimise their sensitivity to direct impacts of physical disturbance. However, increased coral mortality from cyclones is likely to generate large increases in algal turfs.



Shallow-water macroalgal flora will be more sensitive than deeper assemblages. Sensitivity will also depend on thallus morphology and holdfast or anchoring characteristics. For example, large upright seaweeds such as *Sargassum* will be more sensitive to increased wave surge than shorter, low-lying species, so the sensitivity of upright macroalgae as a group is highly variable. Again, storms and consequent coral mortality, are likely to have marked, indirect effects on upright algae by increasing substrate availability.

### *7.2.6.3 Impacts – tropical storms*

Direct damage by tropical cyclones to algal turfs is likely to be minimal. Given their small size, potential impacts on algal turfs include short-term increases in algal productivity and growth due to increases in nutrient availability, from terrestrial runoff (in the case of inshore reefs) or released from storm-disturbed sediments (section 7.2.7). Russ and McCook[164] showed a dramatic increase in algal productivity following a cyclone in the central GBR, apparently due to local increases in nitrogen and phosphorus, which are rapidly taken up by algal turf species. Increases in the biomass of algal turfs may occur if herbivory is reduced. Perhaps the major impact of storms on algal turfs will be due to colonisation of damaged or dead coral. Algal turfs rapidly colonise newly available substrate in a successional sequence, beginning with benthic diatoms, rapidly followed by more-complex morphologies[52,78] (section 7.2.8).

Impacts of tropical cyclones on upright macroalgae vary, depending on habitats and species. Physical wave energy will reduce abundance by dislodging and removing shallow-water species, particularly of delicate forms,[k] but would increase propagation and dispersal for some species[202]. Importantly, however, the large seaweed *Sargassum*, while vulnerable to physical removal, has a spectacular capacity to regrow from minute fragments of holdfast tissue[196]. Newly available substrate, nutrient and sediment loading may increase the abundance of some fleshy macroalgae. Such impacts may produce shifts in species composition, with some macroalgae becoming rare while others bloom (eg *Ulva*).

Negative impacts have not been documented for CCA, and this group of algae may benefit from storms through increases in available substrate due to coral mortality and removal of competing turf and fleshy algae. Potential negative impacts include sediment deposition after storms, and fragmentation, giving rise to living rubble or rhodoliths, although these effects have not been documented from the GBR.

### *7.2.6.4 Adaptive capacity – tropical storms*

The adaptive capacity of algal turfs and some CCA to impacts of tropical cyclones is likely to be high. Turf species have high growth and turnover rates, and rapid replacement of early colonisers may result in pre-disturbance algal composition being achieved before the next storm. Some slower-growing CCA may not recover quickly but, at larger spatial scales, are likely to derive some protection from their morphology.

The adaptive capacity of upright macroalgae is unknown but is likely to be variable and species specific. Some species will regrow from holdfasts or attachment points (*Lobophora*, *Sargassum* Umar et al.[196]), others will regrow from storm-generated fragments (*Dictyota*)[202], but some species may not

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[k] See Rogers[160,161] for examples of cyclone damage on fleshy macroalgal communities at Heron Island.

recover until spores or gametes settle[168]. Rapid recovery in those species with an adaptive holdfast may confer competitive advantages. Two years after cyclone Fran in 1995, *Sargassum* populations had still not fully recovered, whereas populations of other species (eg *Lobophora*) did not suffer major damage from the cyclone[161]. In contrast, recovery of a macroalgal community in a coral reef off Puerto Rico was considered complete within one year of the disturbance[12].

### *7.2.6.5 Vulnerability and thresholds – tropical storms*

Vulnerability of algal turfs and CCA to tropical cyclones is likely to be low, although experimental information is limited. The turfing morphology and creeping habit of algal turf species, and their high growth and reproduction rates, may provide mechanisms for rapid recovery after disturbances. High growth and reproduction rates of some CCA are likely to provide mechanisms for rapid recovery after disturbances. The vulnerability of upright macroalgae is likely to be low but highly variable and taxon specific.

## 7.2.7 Rainfall and river flood plumes

### *7.2.7.1 Exposure – terrestrial inputs*

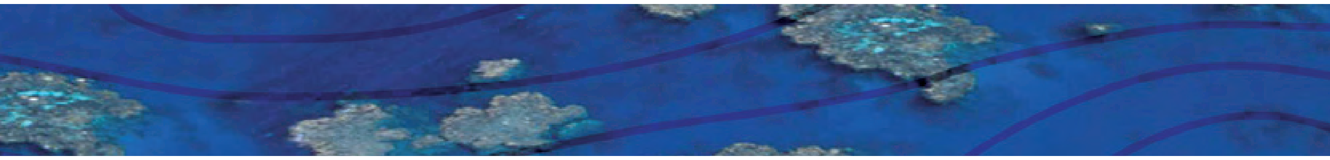
Regional rainfall and river flow show high inter-annual and decadal variability, and currently there is no information about long-term trends towards more fresh water entering the GBR lagoon. However, the intensity of extreme rainfall events might increase as a consequence of climate change. Higher rainfall will produce large freshwater plumes and associated fine suspended sediments, nutrients and other pollutants such as herbicides. Flood plumes already occasionally reach reefs up to 50 km from major river mouths[49]. Exposure of algal turfs, upright macroalgae and CCA to rainfall and river flood plumes will be most pronounced at GBR inshore reefs, particularly during the summer monsoon from December to March, and will depend on the extent and severity of changes in runoff patterns.

### *7.2.7.2 Sensitivity – terrestrial inputs*

Sensitivity of algal turfs and upright macroalgae to terrestrial inputs is moderate to high, complex and variable. Variability in sensitivity will be considerable, due to the species diversity of algal turfs and upright macroalgae, and the complexity of terrestrial inputs: for example, runoff may increase both nutrient supply (enhancing some species) and herbicides (inhibition). Thresholds are likely in competitive balances and in the balance between algal growth and herbivore consumption. The sensitivity of CCA is probably high, as they are sensitive to sediment deposition, eutrophication, pesticides and fresh water. Sensitivity to light reduction varies among CCA species. Competitive interactions and the balance between growth of CCA and their consumption by herbivores are also likely to show thresholds.

### *7.2.7.3 Impacts – terrestrial inputs*

Impacts of terrestrial inputs on the ecology of algal turfs are considerable and variable, although there are few examples from the GBR. Nutrient increases from flood plumes may enhance algal growth, resulting in increased productivity of the whole reef[164]. The expression of enhanced growth as increased biomass will depend on the capacity of herbivores to absorb extra production. Sediment



deposition may reduce growth of some algal species due to hypoxia, light reduction, pesticide inhibition and salinity effects. However, in some reef habitats, algal turf height and biomass are positively related to sediment deposition[152,153]. Impacts also include competitive shifts[l], resulting in changes to species composition, loss of diversity, and changes in ecological functions. For example, a shift in species composition of blue-green algal assemblages from nitrogen-fixing to non nitrogen-fixing species may alter rates of nitrogen fixation. Such shifts may alter chemical microhabitats for coral recruitment.

Runoff may also have indirect effects on algal turfs. While sediment deposition and trapping may be deleterious to some algal turfs, it is likely to be more deleterious to corals or other groups of algae, resulting in changes to overall abundance[132,65]. Indirect effects may also result from enhanced nutrients, which inhibit coral growth and reproduction[204,103,67], and from more turbid waters, which are less suitable for herbivorous fish recruitment[2090,210]. Such indirect effects generally lead to increased relative dominance of algal turfs.

Nutrient increases from flood plumes are likely to enhance macroalgal growth and potentially abundance[84,115,106,171,169,180,173]. Expression of enhanced growth as increased biomass will depend on the capacity of herbivores to consume the extra production[164, 98, 53]. However, growth and reproduction may also be reduced, due to epiphyte overgrowth, light reduction, effects of herbicides and reduced salinity and possible nutrient 'overload' (GBR examples: (Schaffelke et al.[173], Diaz-Pulido and McCook[55]); temperate examples: (Bergström et al.[22]). Sediment deposition (hypoxia) may reduce macroalgal recruitment[196, 64, 94]. These processes may result in shifts in species composition to shorter-lived 'weedy' species, loss of diversity, and carbon and nutrient retention, due to competitive shifts between species and groups[67]. Also, temperate studies suggest perennial, upright algae are less sensitive than simpler, ephemeral algae, and suggest evidence for shifts in species composition[120,121, 122,119], loss of diversity[214], reduced carbon storage and nutrient retention in community[213]. Negative impacts on corals are likely to lead to increased substrate availability for all algal groups.

Potential impacts on CCA include reductions in abundance and diversity, and shifts in composition, for example, to more shade-tolerant but slow-growing species[m]. Such changes are likely to lead to reductions in ecological functions, for example, reef cementing and facilitation of coral settlement. There is potential for complex interactions between algal turfs, sediments, herbivores and the abundance of CCA based on information from the Caribbean (eg Steneck[189]).

### *7.2.7.4 Adaptive capacity – terrestrial inputs*

The capacity to adapt to increased rainfall and river flood plumes is high for turfs as an assemblage, due to the potential for shifts in relative species composition, and flexibility in nutrient processing, but will depend on herbivore consumption. However, the ecological roles of algal turfs may have less capacity to adapt. For example, increased biomass of turfs and subsequent sediment trapping will limit coral recruitment.

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[l] For example, nutrients: nitrogen-fixing cyanobacteria affected by N and P balances; *Cladophora* tolerant to freshwater exposure; fresh water carries silicic acid, which may favour diatom blooms[56,197,6].

[m] Correlation studies suggest runoff has impacts on species composition[66]. Experimental studies have demonstrated negative effects of sediments and diuron [a herbicide regularly found in low concentrations in GBR coastal waters[178]], on CCA[26, 189, 82].

The adaptive capacity of upright macroalgae to terrestrial inputs is probably moderate to high, and positive effects are expected. However, this adaptation is likely to involve shifts in composition, involving losses or shifts in diversity and ecological roles. Shifts in species composition of upright macroalgal communities will reflect adaptive capacity of individual species to different salinity, nutrient, herbicide and sediment conditions.

There is a lack of empirical data on the adaptive capacity of CCA to terrestrial inputs, but it is likely to be low due to slow growth rates of some species and competition from turfs and upright macroalgae. This is supported by evidence of low abundance and diversity in areas affected by high runoff[66].

### *7.2.7.5 Vulnerability and thresholds – terrestrial inputs*

Algal turfs and upright macroalgae, particularly from inshore reefs, are moderately to highly vulnerable to terrestrial inputs. Physiological and ecological impacts of runoff of terrestrial nutrients, sediments and pollutants are likely to be species specific, leading to changes in species composition. CCA are highly sensitive to terrestrial inputs, are likely to have low adaptive capacity, and therefore are highly vulnerable to increased inputs of terrestrial material.

## 7.2.8 Increased substrate availability due to coral mortality

### *7.2.8.1 Exposure – increased substrate availability due to coral mortality*

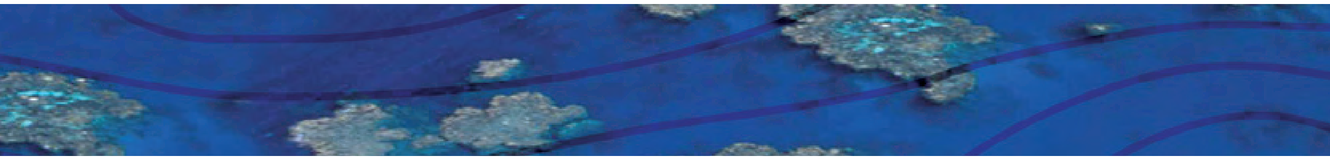
Exposure of algal turfs, upright macroalgae and CCA to increased substrate availability due to coral mortality is considerable. Widespread coral mortality is extremely likely, due to mass coral bleaching and other causes of mortality directly or indirectly related to climate change (Hoegh-Guldberg et al. chapter 10).

### *7.2.8.2 Sensitivity – increased substrate availability due to coral mortality*

Algal turfs are extremely responsive to increased substrate availability[52,54]. There is considerable potential for thresholds, due to rapid colonisation of new substrate and positive feedbacks. Upright macroalgae are also very likely to benefit from newly available substrate, but their response may be moderated by competition with the faster-colonising turf algae and by herbivory. Some CCA are rapid colonisers of any bare space, whereas others will be strongly dependent on low levels of competition with algal turfs and significant herbivore impacts. There is considerable potential for thresholds, due to rapid colonisation of available substrate and the potential for saturation of herbivore consumption capacity. For a given algal growth rate, increased area of algae may result in growth rates that overwhelm the capacity of a given herbivore population to control upright macroalgal abundance[211].

### *7.2.8.3 Impacts – increased substrate availability due to coral mortality*

Among the impacts of increased substrate availability due to coral mortality is a massive increase in the area and abundance of turf algae and upright macroalgae (examples from the GBR: (Diaz-Pulido and McCook[52,54]; pers obs for 2006 bleaching); non-GBR: (Hughes[91], Ostrander et al.[144], McClanahan et al.[129], Aronson and Precht[8]). Turf algae are rapid colonisers of dead and injured corals[148,58,52,78]. Turf areas may undergo succession towards more upright macroalgae, because turf algae provide a more suitable substrate for macroalgae than live coral[52,54]. The extent of this replacement will depend strongly on levels of herbivory and other factors such as nutrient availability.



Increases in macroalgal colonisation will increase coral–algal competition and inhibit coral recruitment and recovery, reducing overall reef resilience and stabilising phase shifts from dominance by corals to dominance by turf and upright macroalgae[24,97,25]. Many of the climate change stressors will increase the competitiveness of turf algae over CCA, leading to further inhibition of coral recruitment. This may generate positive feedback effects for turfs and, subsequently, for upright macroalgae, especially if herbivory is low. There is also potential for positive feedback through algal-derived increases in dissolved organic carbon, which damages coral health and may inhibit coral recovery[181]. Shifts are also likely in species composition and ecological functions of turf and upright algae (eg primary production, nutrient fixation), along with changes in habitat creation[n] and herbivore palatability.

#### *7.2.8.4 Adaptive capacity – increased substrate availability due to coral mortality*

Algal turfs and upright algae (based on limited knowledge for the latter group) are likely to increase in abundance, but species composition of assemblages is likely to shift to more 'weedy' species. The capacity of the ecosystem to adjust to these changes is limited and uncertain, and will depend on other aspects of resilience of the ecosystem, such as eutrophication and herbivore abundance. The resilience of the ecosystem is likely to be significantly reduced by upright algal assemblages. Abundant herbivores may prevent this dominance, allowing persistence of crustose forms, with long-term benefits to ecosystem recovery and adaptation.

There is no information on the adaptive capacity of CCA to increased substrate availability and the subsequent succession of algal assemblages, but given the important ecological roles of CCA, this is likely to be critical to longer-term adaptive capacity and resilience of the ecosystem.

#### *7.2.8.5 Vulnerability and thresholds – increased substrate availability due to coral mortality*

Algal turfs, upright macroalgae and CCA as groups will benefit from increases in substrate availability due to coral mortality. However, in the long term, the natural composition of algal turfs and CCA may be highly vulnerable, due to competitive shifts, to preferential feeding by herbivores, and potentially significant loss of functional diversity. These changes are likely to have major impacts on ecosystem vulnerability as a whole. Ultimately, the response of each algal functional group to increased substrate availability will depend upon the overall characteristics of the given location.

## 7.3 Linkages and summary

### 7.3.1 Linkages and summary of major vulnerabilities to climate change

Assessing the vulnerability to climate change of any group of benthic algae of the GBR is severely hampered by the general dearth of eco-physiological studies, either from the GBR or from tropical regions more generally. Further, climate change will affect algae not only directly (eg physiological effects of increased sea temperatures) but also indirectly. For example, climate change impacts on corals or herbivores will have major effects on the area and biomass of algae. For these reasons, the

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[n] Beds of upright algae such as *Sargassum* provide important habitat structure in extensive areas of the shallow inshore GBR (eg Martin-Smith[128]); *Halimeda* beds form extensive habitats in several inter-reef areas of the GBR[40].

following treatment is based not only on the information available from the GBR and other tropical regions, but also on inferences drawn from better studied temperate species, and from expert opinion. The complexity and lack of information mean that even loose predictions are not realistic, and we aim instead to outline potential scenarios for consideration.

### *7.3.1.1 Turf algae*

Algal turf assemblages are ubiquitous and particularly diverse in coral reefs. On shallow reefs of the GBR, a single square centimetre may contain more than 20 species of benthic algae[52]. This high species diversity complicates any interpretation of the impacts of climate change on algal turfs, particularly when looking at impacts at large spatial and temporal scales. Even more than for upright macroalgae and CCA, the assessment of vulnerability for algal turfs of the GBR is seriously hampered by a lack of information on the taxonomy, species composition, diversity, and spatial and temporal dynamics of this group of macroalgae.

Algal turfs are likely to be affected by both direct and indirect climate stressors. The vulnerability of algal turfs to direct impacts is highly variable, ranging from low to moderate, and, in some situations, some stressors are likely to have positive effects on some species (Tables 7.3 and 7.4). For example, if terrestrial runoff of nutrients increases as a result of climate change, this may enhance productivity and growth of some taxa or individuals. This may, in turn, cause shifts in competitive balance, resulting in shifts in species composition of the turf assemblage to more 'weedy' taxa. Similarly, increases in temperature and $CO_2$ may initially benefit species with wide temperature tolerances[31] and carbon-limited species, inducing species shifts with unknown consequences. Increased UVB radiation may reduce photosynthesis of some species in shallow waters, while other taxa may gain a competitive advantage from such increases (eg species that produce high levels of UV-absorbing compounds such as mycosporine-like amino acids, provided there is adequate nitrogen availability). Thus, impacts on individual species are likely to be variable and complex (Figure 7.2), but will most likely generate shifts in species composition.

Despite the lack of studies on the adaptive capacity of algal turfs to global climate change, it seems probable that the adaptation potential of turfs, as an assemblage, will be moderate to high. Turf species have high rates of colonisation, growth and reproduction, and are quite resilient to disturbances[117,191]. For example, more-frequent cyclones may disturb a turf assemblage, initially shifting community structure to stages dominated by early colonisers such as benthic diatoms[48]. However, this early stage is rapidly replaced by filamentous forms characteristic of 'typical' algal turfs (ie they have a strategy of 'recovery' sensu[187,191]). At a temporal scale of weeks to months, physical disturbances may not lead to major overall impacts on the turf assemblage, but may result in shifts in species composition, depending on magnitude and duration of disturbance. This constitutes ecological adjustment, in the sense that turf algae are likely to persist, but the specific combination of turf species is likely to be quite vulnerable within a location.

Significant interactions between stressors, and changed competitive relationships with other functional groups of algae, are also likely. Such interactions might lead to large shifts in species composition with little potential for adaptation within particular habitats. For instance, increased frequency of cyclones may reduce the abundance of canopy-forming *Sargassum* (which is fertile during the cyclone season) with long-lasting consequences for the understorey turf assemblage. Rapid and prolonged exposure of the understorey to high light may lead to photoinhibition, causing decreased productivity and growth

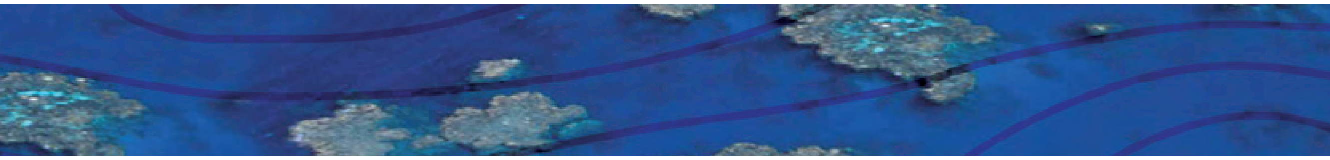
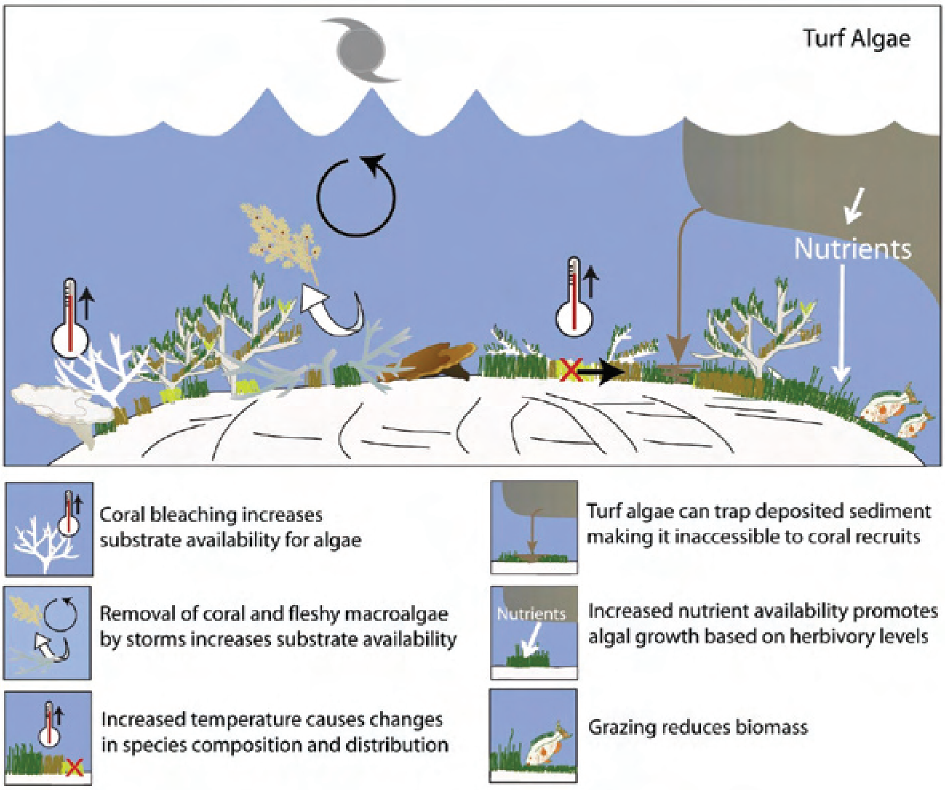


***Figure 7.2*** *Global climate change impacts on algal turfs*

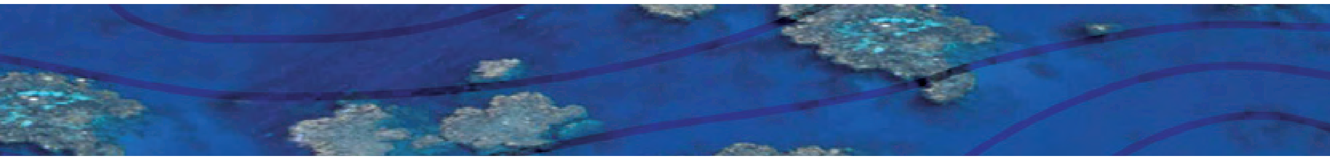


and, in the longer term, leading to a shift to more light-tolerant taxa. There are no reported cases of extinctions of turf algal species, although the flora is not well known and difficult to study on the scale of the GBR. Nonetheless, we consider climate stressors unlikely to lead to extinction of turf species.

The direct effects of climate stressors on algal turfs are likely to be strongly regulated by interactions between substrate availability, herbivore grazing and nutrient supply. Increasing sea temperatures are expected to cause massive coral mortality[89] (Hoegh-Guldberg et al. chapter 10), followed by extensive algal colonisation of dead coral substrata, resulting in marked increases in cover and biomass of algal turfs[52]. Climate change impacts on herbivore populations, both invertebrates (urchins, molluscs, crustaceans) and vertebrates (fishes, marine turtles), will have profound consequences for the composition and abundance of turfs. The proposed impacts of climate change on herbivore abundance include increased food availability (due to algal overgrowth of dead coral[159]) but ultimately a decrease in abundance due to the loss of coral habitat and shelter (due to coral mortality and breakage; see Munday et al. chapter 12). The former impact is a consequence of algal abundance, not a cause: that is, increased herbivore abundance can only moderate, but not negate, increased algal abundance. The effects of habitat loss on herbivores are likely to be greater and longer term than any food-driven increases, resulting in net decreases in algal consumption. This may contribute to feedback effects, as algal abundance inhibits recruitment and recovery of corals[132].

***Table 7.3*** *Generalised predictions of the characteristics of future GBR algal communities affected by climate change, based on vulnerability assessments, and comparison to present-day characteristics**

| Present | Future |
|---|---|
| **Habitat characteristics** | |
| • Dynamic communities, infrequent disturbance leads to decrease of coral cover and subsequent recovery<br>• Substrate availability dynamic due to infrequent and local disturbance<br>• Some inshore reefs with sustained low coral cover | • Frequent and chronic disturbance leads to low coral cover, especially in shallow water<br>• Higher substrate availability for algal colonisation over longer periods of time and larger spatial scales |
| High herbivore abundance, sufficient to control macroalgal biomass (except for inshore reefs with high standing stocks of macroalgae) | Low herbivory due to low habitat complexity and turbid water, insufficient to control macroalgal biomass |
| **Characteristics of algal communities and species** | |
| • Patchwork of algal communities, controlled by herbivory, substrate and nutrient availability<br>• Generally higher algal biomass inshore | • Generally higher algal cover, high biomass in areas with low herbivory<br>• Southward expansion of distribution ranges |
| Mix of canopy-forming, understorey, turfing and encrusting species inshore; mainly turf and CCA offshore | Short, low-lying species (turf and short upright macroalgae inshore), turf and some CCA offshore |
| • Mix of calcified and uncalcified species (more uncalcified inshore)<br>• Low CCA inshore, high CCA offshore | • Uncalcified dominate<br>• Low CCA everywhere, weak skeletons |
| • Mix of species with perennial, annual and ephemeral life cycles, likely controlled by seasonal triggers<br>• Inshore: Fucales growing and reproducing in summer form canopies; understorey of turfs and diverse green and red algae; sporadic spring blooms of brown algae<br>• Offshore: turf, CCA, *Halimeda*, low macroalgal abundance, no distinct seasonality, local ephemeral blooms of greens, cyanobacteria or *Chrysocystis* | • Species with ephemeral life cycles prevail, dominance of fast-growing weedy species that recover and colonise quickly after disturbance, algal blooms after substrate release |



| Present | Future |
|---|---|
| Mix of species with different:<br>• temperature tolerances (some occur only as winter annuals)<br>• UV tolerances and light requirements (variation along inshore/offshore, within-canopy and depth gradients)<br>• nutrient requirements (variation along inshore/offshore gradients; species with higher nutrient requirement generally inshore, apart from some *Halimeda* species) | Communities dominated by species with:<br>• High temperature tolerance or generalists, loss or southward shift of winter annuals<br>• High UV tolerance and broad light requirements (strong fluctuations in water column light attenuation due to more intense floods and storms alternating with extended drought conditions)<br>• High nutrient demand, ephemerals, bloom-forming species (variable nutrient availability due to alternation of floods and storms with extended droughts) |

* Note: Predictions are very uncertain, and likely to vary considerably with conditions.

***Table 7.4*** *Summary of the responses of macroalgae of the Great Barrier Reef to global climate change**

| Climate stressor | Algal turfs | Upright macroalgae | Crustose calcareous algae |
|---|---|---|---|
| Change in ocean circulation | ↑↓ | ↑↓ | ↑↓ |
| Increased water temperature | ↑↓ | ↑↓ | ↑↓ |
| Increased $CO_2$ and acidification | ↑↑↓ | ↑↑↓ (fleshy)<br>↓↓ (calcified) | ↑↓↓ |
| Light and UV | ↑↓↓ | ↑↓↓ | ↑↓ |
| Sea level rise | ↑↑↓ | ↑↑↓ | ↑↑↓ |
| Tropical storms | ↑↑ | ↑↓ | ↑– |
| Terrestrial inputs | ↑↓ | ↑↓↓ | ↑↓↓ |
| Increased substrate availability | ↑↑↓ | ↑↑↓ | ↑↓↓ |

Upward arrow (↑) represents a beneficial effect. Downward arrow (↓) represents a detrimental effect (eg due to indirect impacts or impacts at the level of the community). Dash (–) represents a neutral effect for algae.

* Note: The table is based on vulnerability assessments and is inherently speculative.

Healthy populations of herbivores will reduce the risks of runoff impacts on algal turfs, and minimise the chances of shifts from communities dominated by healthy, productive turf assemblages to less desirable communities[92]. Loss of herbivores has been shown to cause self-shading and a decline in mass-specific productivity[34,35,36]. It is also important to recognise that, if significant shifts in composition of turfs do occur, this may be assumed to result in changes in the ecological roles and effects of the turfs on the ecosystem as a whole. Thus, for example, trophic and nutrient dynamics may change, or an overabundance of unpalatable or toxic algae may inhibit coral recruitment, in effect stabilising declines in coral populations. Studies from the GBR have shown that interactions between benthic algae (especially turf algae), corals, nutrients and herbivores are complex[103,92,98,53], so predicting the effects of global climate change on each of these factors (and others), and their interactions, will require considerable care.

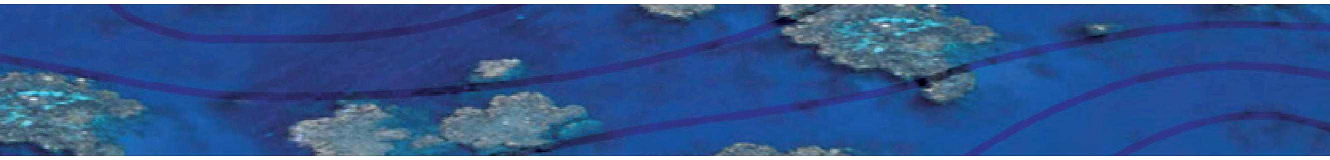
There is also a significant risk that, even without declines in herbivore populations, massive increases in the area of algae may sufficiently increase total algal production, such that it exceeds the capacity of existing herbivores to consume it. Such saturation of herbivore consumption will in effect release algal abundance from herbivore control (eg Williams et al.[211], McCook unpublished data), potentially reducing the suitability of habitat for herbivores. Further, under such circumstances, herbivores may feed preferentially on palatable species, such as *Polysiphonia* and *Sphacelaria*. This may lead to a positive feedback, increasing the relative abundance of unpalatable and/or toxic taxa, such as cyanobacteria or larger, fleshy macroalgae with chemical deterrents, with a potential further loss of functional diversity.

However, the vulnerability of algal turfs to such indirect effects is difficult to assess, given our poor understanding of the long-term impacts of coral disturbances on the dynamics of algal species (the result of a lack of detailed long-term monitoring of algal communities). In simple terms, algal turfs as a group will strongly benefit from increases in substrate availability due to coral mortality. In the long term, however, the natural composition of algal turfs may be highly vulnerable, due to competitive shifts and to preferential feeding by herbivores.

We conclude that the vulnerability of algal turfs to climate change is highly variable and unpredictable, and lack of information severely reduces the ability to make accurate predictions. Nonetheless, we suggest that turfs as a group have the potential to adapt (ie adjust) to the changing environment, provided herbivore populations remain adequate. However, shifts in species composition of turf assemblages are likely. The consequences of these shifts for the ecological roles of algal turfs, and hence for the vulnerability of the ecosystem, are difficult to predict, but may be more extreme than postulated above. More serious than the vulnerability of turfs as a group is the vulnerability of reefs to shifts from corals to turfs (as has already happened in the Caribbean). The adaptive capacity of algal turfs makes them a threat to corals and, hence, increases the vulnerability of coral reefs as a whole.

### *7.3.1.2 Upright algae (fleshy and calcified)*

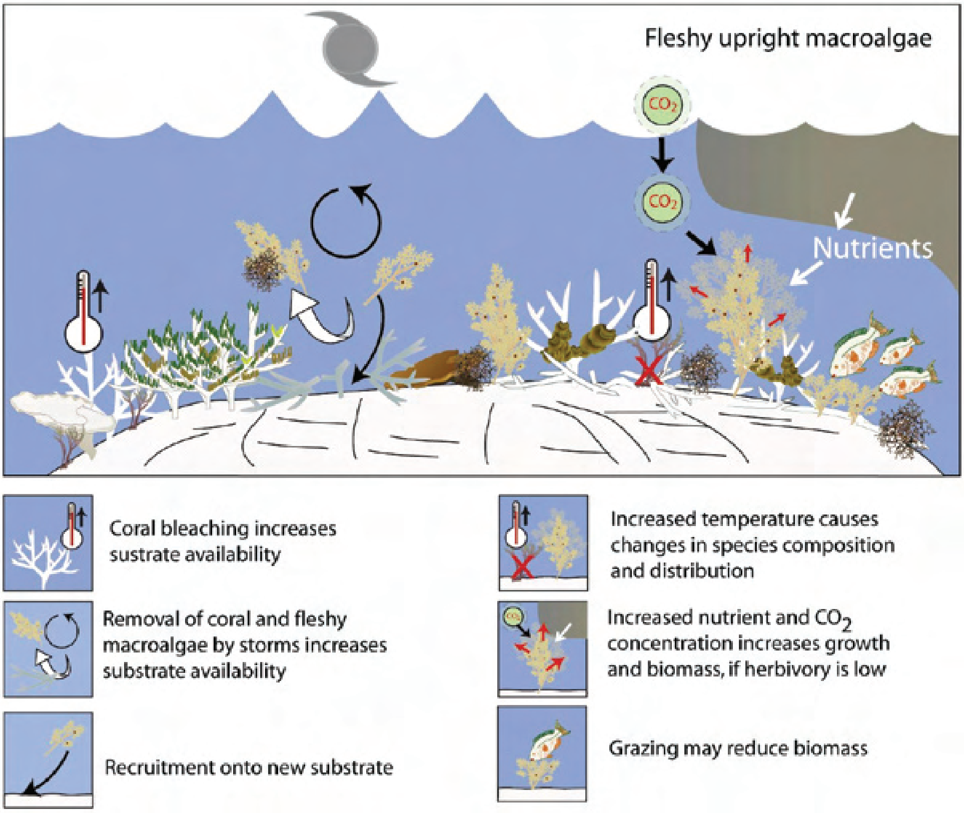
Upright algae in the GBR occur in a wide range of habitats, but predominantly in shallow (to approximately 20 metres depth) or intertidal waters; the notable exception being the deep-water Halimeda beds. The diversity of the algal flora of the deep GBR lagoon floor is currently being explored (Skelton pers comm), but there is little ecological information available. Shallow-water habitats are likely to be exposed to a range of climate change stressors, including more storms and associated terrestrial runoff, higher temperatures and UV radiation.



There are currently no studies demonstrating the effects of changing climate on GBR upright macroalgae. We suggest that some climate change stressors will have positive effects on productivity, growth, reproduction and abundance of upright macroalgae (Tables 7.3 and 7.4). These include sea level rise (in coastal areas without artificial structures such as sea walls), temperature and increased $CO_2$ availability (although the latter two are likely to be detrimental to calcified algae). These stressors would positively interact with the expected higher availability of substrate for algal colonisation, caused by climate-related coral mortality and rises in sea level (Hoegh-Guldberg et al. chapter 10 and Fabricius et al. chapter 17, Figure 7.3). Other climate-derived stressors, such as storms, increased terrestrial runoff, UV radiation, and changed circulation patterns, will have variable or no effects, depending on the species' biology and ecology.

As for turf algae, we do not expect climate change to cause serious direct mortality of macroalgal species or communities, but rather to lead to significant changes in benthic community composition. This would be mainly through direct effects such as changes to productivity, growth and reproduction. Even slight changes in temperature, or other factors, are likely to lead to species- (or ecotype)-specific changes in optimal production, distribution, and possibly the seasonal timing of growth

***Figure 7.3*** *Global climate change impacts on upright macroalgae*



and reproduction. These changes may generate shifts in competitive relationships, in turn causing transitions in community composition[31,79]. Southward immigration of species or ecotypes is likely, especially in the southern GBR. Interactions between climate change stressors are probable but poorly understood. For example, in temperate algal species, UV tolerance was higher at higher temperatures, up to a species-specific threshold[90].

These direct effects are likely to be intensified by indirect effects of climate change on other organisms that interact with upright algae, such as herbivores, and competitors, especially corals[135,111,119,175]. Any climate change stressor that has detrimental effects on coral health will indirectly benefit most upright macroalgae. Macroalgal biomass may reduce coral growth, reproductive output and recruitment[24,194,134,111,98,67]. Saturation of algal consumption by herbivores may accentuate such changes[211], stabilising macroalgal dominance. Further feedback effects may include selective overgrazing of unpalatable algae, and loss of coral habitat for herbivores.

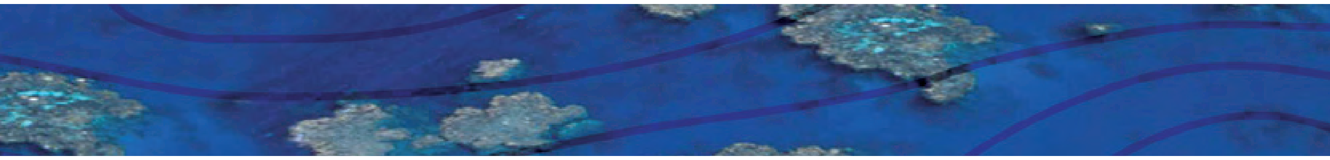
It is likely that GBR upright algae may adapt to several stressors, such as increasing temperature and UV radiation, given their assumed existing tolerance. At the ecosystem level, however, such adaptation is likely to enhance, rather than reduce phase shifts (McCook et al. chapter 4;[141, 21]). The species diversity of GBR macroalgae is poorly described and the genetic diversity undescribed, but it is possible that high diversity and/or functional redundancy may provide some insurance against community transitions caused by climate change (Harrington et al.[80] for plants and insects, Reusch et al.[155] for seagrasses).

We conclude that, as a group, fleshy upright macroalgae in the GBR are likely to benefit from many of the environmental changes brought about by climate change. Adapted species may find more space to colonise and may grow better due to more optimal temperatures and nutrient and dissolved inorganic carbon availability, provided they are not disturbed by increasing storm intensity or frequency. However, future macroalgal communities are likely to change in composition as less adapted species are excluded and biological interactions change. Higher biomass and altered species composition of fleshy upright algae on coral reefs may change competitive interactions with corals and lead to impairment of coral recruitment, which would indirectly further reduce coral resilience (McCook et al. chapter 4;[135]). In habitats other than coral reefs, the interactions of upright macroalgae with other major ecosystem builders (eg seagrasses) are less well understood and cannot be predicted with any certainty.

In contrast, calcified upright macroalgae are likely to be adversely affected by climate change. Higher temperature, nutrient and $CO_2$ availability and associated acidification of the tropical sea will affect calcification, outweighing any positive effects on algal productivity. Disturbance of these very important components of the GBR ecosystem is likely to lead to serious cascading effects, such as loss of unique habitats (eg *Halimeda* banks[60,147,126]) and decreased production of calcareous sediments.

### 7.3.1.3 Crustose calcareous (calcified) algae

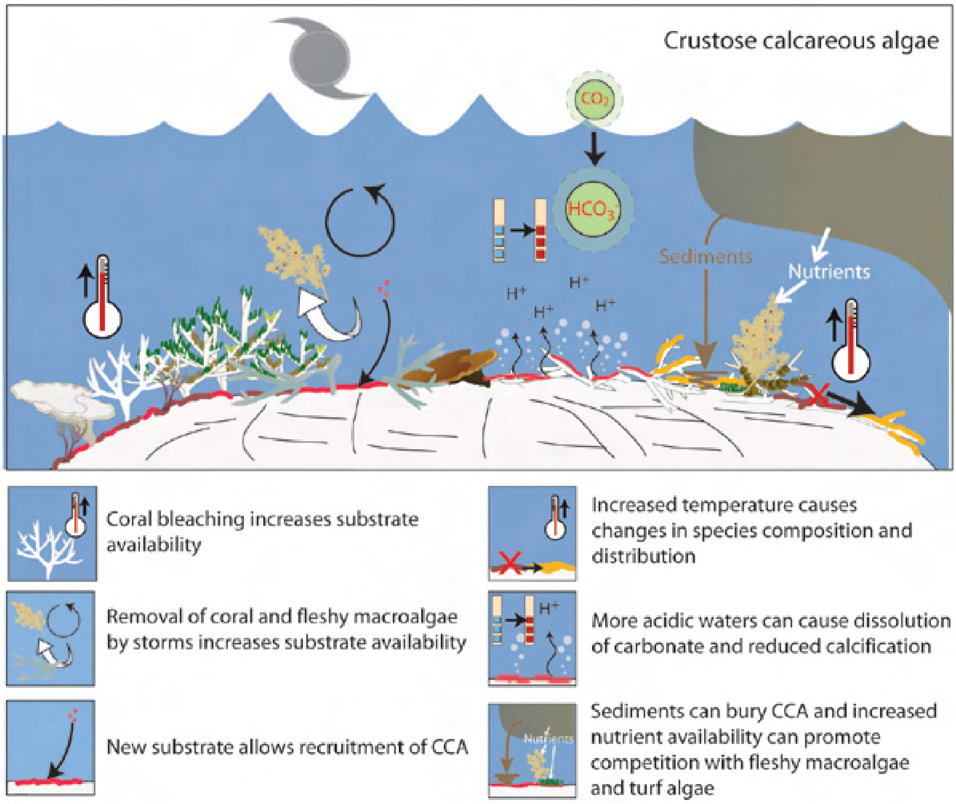
Assessing vulnerability for CCA is, as for turf and upright macroalgae, a difficult task due to the taxonomic heterogeneity, variety of life histories and ecological roles within the group. Thin, 'weedy' CCA have high growth rates and rapid colonisation and are therefore likely to respond differently to climate changes compared with thick, slow-growing CCA. CCA are exposed to a variety of climate stressors, but our analyses suggest that changes in ocean chemistry through acidification and increasing runoff are likely to be the most harmful.



The vulnerability of CCA to the impacts of some climate stressors is probably low. Increased frequency and intensity of storms will have little effect, given the hard, calcareous nature of these algae. The shallow-water CCA flora is also quite well adapted to high UV radiation, and it has been recently suggested that calcification may provide extra protection against increasing UV radiation[18]. The impacts of increasing substrate availability due to coral mortality are difficult to predict, given the lack of long-term monitoring of the dynamics of this group. Cover of CCA, particularly the 'weedy' species, may increase with increasing substrate availability due to coral mortality, but this will be moderated by competition with other algal groups, less affected by acidification. Direct impacts of rising sea temperature on the abundance of CCA are not known but are likely to be minor. However, rising temperatures may have significant, indirect negative impacts, such as enhancing diseases. Increases in disease among many groups of calcified organisms (CCA, corals, sea urchins and lobsters) but not in other groups (eg fishes[205]) may reflect cumulative impacts from a range of stressors, such as temperature, UV radiation and $CO_2$.

In contrast, CCA are highly vulnerable to the direct impacts of increasing atmospheric and hence sea surface $CO_2$ and the consequent slight increase in bicarbonate, and decrease in pH and in carbonate concentration (Figure 7.4).

***Figure 7.4*** *Global climate change impacts on crustose calcareous algae*



Increasing runoff may have varied effects on CCA, and their vulnerability will depend on their location on the continental shelf. Inshore CCA are highly exposed, due to their proximity to the source, and moderately vulnerable to increased nutrients, compared with offshore CCA flora. Longer term impacts of runoff will depend strongly on competition with turfs and macroalgae, in turn also influenced by herbivore abundance.

The overall potential for adaptation of CCA to global climate change is unknown. It is likely that CCA will adapt to increasing impacts of storms, sea level rise and increasing UV radiation. However, the potential for adaptation to acidification is likely to be low. Crustose algae as a group are likely to persist in the GBR, but at significantly reduced abundances, and with ecologically significant shifts in species composition, distribution and function. Given their apparent importance to coral recruitment, such changes are likely to significantly reduce the adaptive capacity of the ecosystem as a whole.

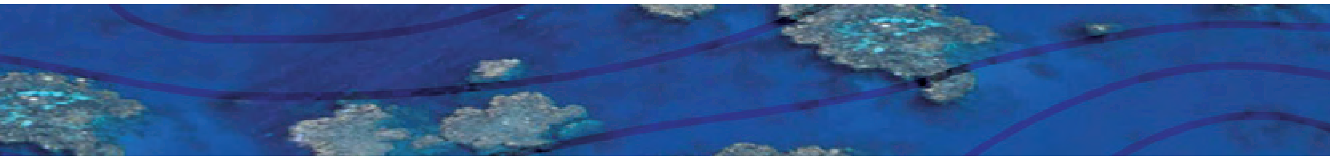
## 7.4 Recommendations

### 7.4.1 Potential management responses

As with all climate change impacts, the most powerful, and cost-effective, management strategy is to minimise the extent of the impacts, by abatement of greenhouse gas emissions. Although obvious, and beyond the scope of marine park managers, greenhouse gas emissions are important to emphasise, especially as they are common to all climate change impacts. Measures that reduce the impacts of increased $CO_2$ concentrations, and therefore ocean acidification, are probably particularly important, given the vulnerability of CCA to acidification, and the potential significance of CCA to overall ecosystem resilience.

Management responses to enhance resilience of natural macroalgal populations on the Great Barrier Reef will essentially overlap with those that protect coral populations and enhance general ecosystem resilience. To protect the natural abundance and composition of macroalgae, it is crucial to protect populations of herbivores, and minimise terrestrial runoff and other sources of nutrient, sediment or toxicant pollution. These measures will not only benefit corals directly but will also reduce the feedback impacts of increased abundance and changes in algal community composition. Similarly, any measures that serve to minimise the extent and severity of coral mortality events will also reduce the extent of algal colonisation, and vulnerability to subsequent shifts in community structure.

Finally, there is clearly a need for more information on the potential nature and extent of climate change impacts on tropical algal assemblages. While this is generally true for all groups, the taxonomic and ecological diversity of the algae, and the lack of knowledge regarding the composition, physiology and ecology of algal assemblages is markedly greater than that for other major groups of benthic organisms in the GBR.



### 7.4.2 Further research

There is a general need for more information about almost all aspects of climate change effects on most types of algae. However, several areas are likely to be particularly important in recognising and assessing emerging impacts, or to be more significant for the GBR ecosystem as a whole. Given the likely importance of shifts in community composition, there is a strong need for better baseline descriptions of current species distribution and abundance patterns of all macroalgal groups along the whole GBR, including groups, such as turf algae and CCA, that are difficult to identify in the field. Without such descriptions, we are unlikely to detect or understand many community shifts.

Given the important roles that CCA play on reefs, and the potentially dramatic effects of acidification on calcification by CCA, research on the impacts of $CO_2$ and ocean acidification on CCA is urgently needed, as are studies of other stressors on CCA. Similarly, the few studies on *Halimeda* species and other upright calcifying algae suggest that calcification will be inhibited, and further studies are needed.

Finally, better understanding of the ecological interactions between algae, coral populations and herbivores (mainly fish) under climate change scenarios is required. There is a need for experimental studies under climate change conditions (eg high temperature, low pH) to predict future algal colonisation and succession after coral mortality, and the effects of different algal assemblages on coral recruitment. Similarly, we cannot assume that the critical influence of herbivorous fishes on coral–algal interactions will be the same under changed climate conditions. A strong understanding of how coral–algal–herbivore interactions will change under climate change scenarios will be critical to future efforts to manage for resilience of the Great Barrier Reef, and of tropical habitats generally.

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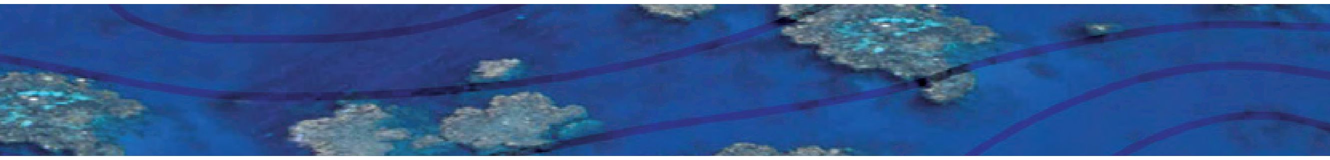

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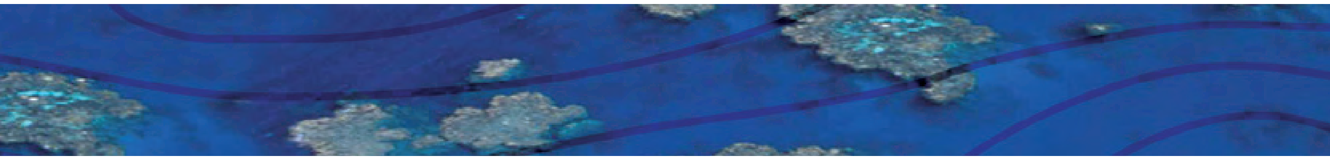

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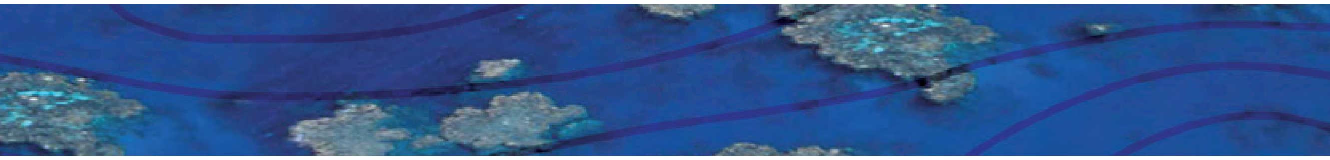

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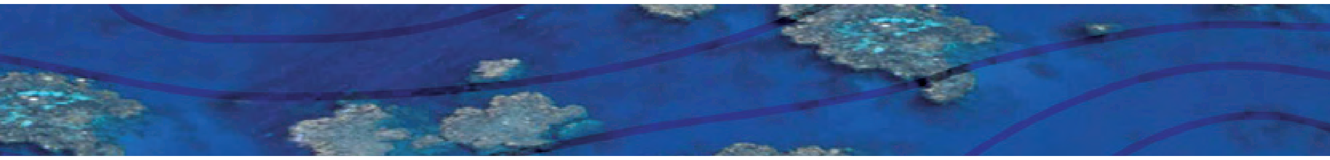

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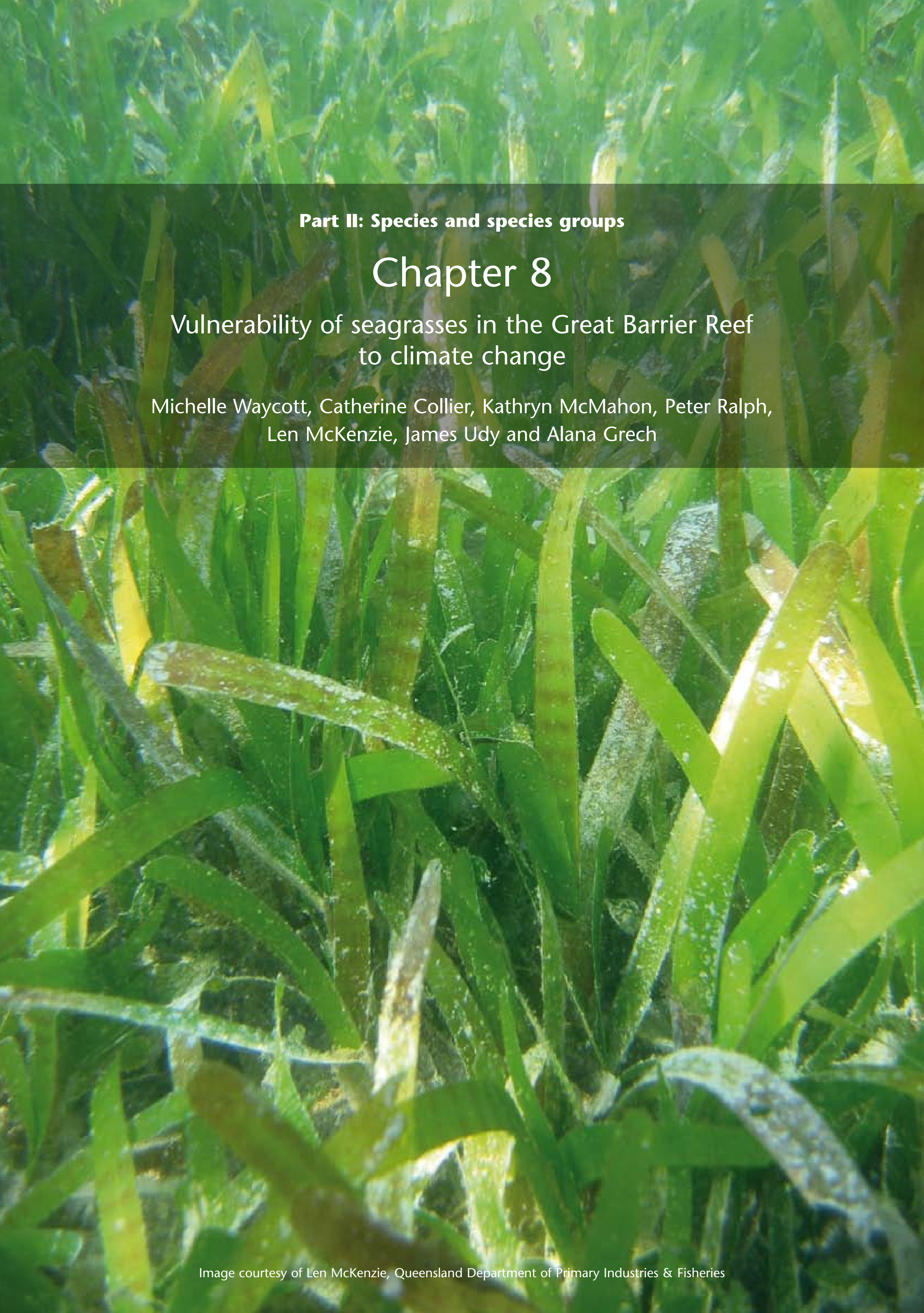


## Part II: Species and species groups

# Chapter 8

## Vulnerability of seagrasses in the Great Barrier Reef to climate change

Michelle Waycott, Catherine Collier, Kathryn McMahon, Peter Ralph,
Len McKenzie, James Udy and Alana Grech

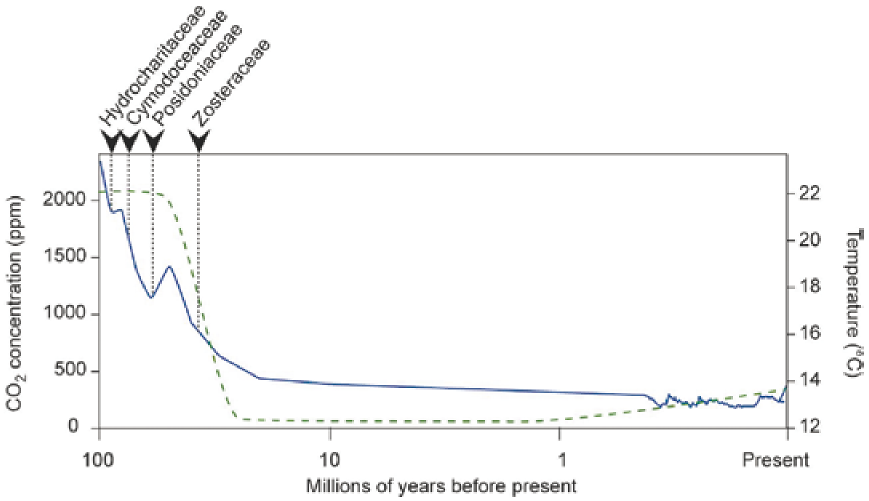
Image courtesy of Len McKenzie, Queensland Department of Primary Industries & Fisheries

## 8.1 Introduction

Seagrasses are flowering plants and, along with mangroves, have greater affinities to terrestrial plants than other marine macrophytes such as algae. Approximately 55 species of seagrass occur in five different plant families and represent at least three independent evolutionary lineages[85,149]. Thus, seagrasses are not a taxonomically unified group but a 'biological' or 'ecological' group[85,149]. The evolutionary adaptations required for survival in the marine environment have led to convergence in morphology[149]. Seagrasses evolved under differing ambient $CO_2$ and temperature conditions (Figure 8.1) so may have different tolerances to changing environmental conditions. A wide range of tolerances across marine environments exist amongst the extant diversity of seagrasses, reflecting their substantial adaptive capacity as a group.

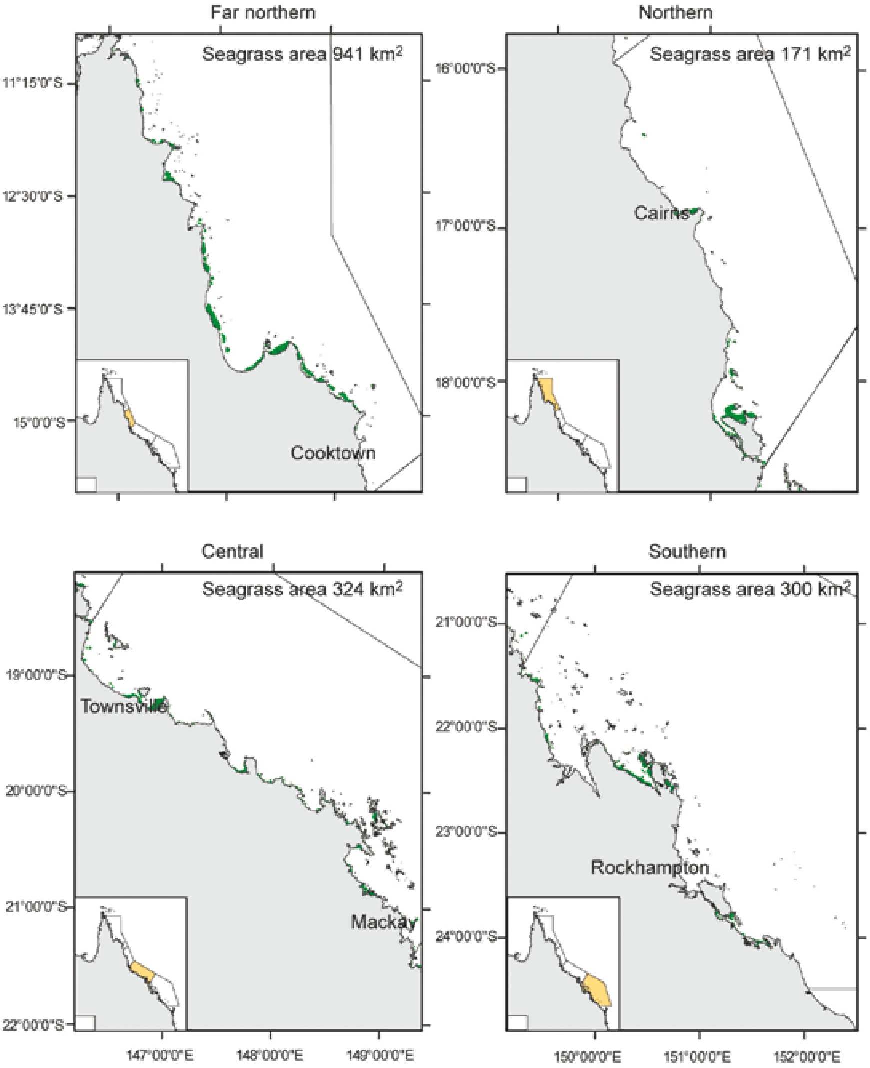
Seagrass diversity in Australia is amongst the highest in the world, in part due to the overlap of already diverse tropical and temperate floras[141,31]. The bays, estuaries, lagoons and reef platforms of the Great Barrier Reef (GBR) region provide habitat for 12 seagrasses including one endemic species, *Halophila tricostata*. The seagrasses of this region are typically found growing in waters less than ten metres below mean sea level. However, some species of the genus *Halophila* can be found to depths of 56 metres[82,25]. Shallow and intertidal seagrass meadows are influenced by coastal topography and shelter, as a result, most larger seagrass meadows are found in north facing bays and estuaries that are protected from the dominant south-easterly winds. The highest densities of seagrass occur between Princess Charlotte Bay and Cairns (13.5 to 17 °S) and below Rockhampton (23 °S). Seagrass meadows are sparse north of Princess Charlotte Bay and south of Mackay in the area where tidal velocities are high. The total area of seagrass habitat along the Queensland coast has remained relatively stable during the past 5 to 10 years.

***Figure 8.1*** *Timeline of seagrass evolution showing the current estimated time of origin of major seagrass lineages, estimated and measured atmospheric $CO_2$ concentration (solid line) and mean global ambient temperature (dashed line) (adapted from Orth et al. 2006)*



The mapped area of seagrass is approximately 1741 km$^2$ (Figure 8.2), while best estimates of total area of seagrass meadows along the east coast are 5668 km$^2$ of intertidal and shallow subtidal habitat (down to 15 metres water depth)[66,4,83,84,91,26,27,28,29,30,92,93] (Queensland Department of Primary Industries and Fisheries unpublished data) (Figure 8.2). The area of seagrass meadows in reef lagoon waters of the GBR deeper than 15 metres may be as high as 40,000 km$^2$ [25], however these seagrasses are little studied. We present the seagrass areas of the GBR in four regions to facilitate discussion regarding the different general environments seagrass occur.

***Figure 8.2*** *Four regions of the GBR with total mapped seagrass distributions plotted (green). Calculated area of mapped seagrass within each zone is nominated. Data is sourced from all mapping studies available and integrated over time (1981 to 2004)*



As productive coastal habitats that typically connect terrestrial, estuarine, saltmarsh and mangrove habitats, seagrass communities are recognised as having a high value globally (reviewed in Orth et al.[109]). Seagrasses act as the foundation of a diverse community with numerous ecological roles; primary production, habitat for other species of plants and animals, food for micro, meso and mega herbivores (including turtles and dugongs), sediment stabilisation, biochemical modification of their local environment and hydrodynamic modifiers. Another highly valued ecosystem service is their role in nutrient cycling[35].

Tropical seagrass meadows have been documented to create habitat complexity compared with unvegetated areas – providing up to 27 times more habitable substrate[115] – as well as providing refuge and food for a range of animals. At least 20 species of prawns (mostly commercially important juveniles) can be found in seagrasses of the GBR in densities eight times that of adjacent bare areas[23,80,24]. Seagrass meadows are also crucial habitat for at least 134 species of fish, predominantly gobies, leatherjackets, pony fish and trumpeters[23,80,24].

In the GBR, the abundance of fauna occupying seagrass meadows correlates strongly with seagrass biomass or living space (leaf area)[103,61,74]. The fish and prawns occupying these seagrass meadows are predominantly carnivorous, feeding not directly on the seagrass but on a range of fauna occupying the meadows including amphipods, isopods, gastropods and copepods[145,74]. These smaller invertebrates form an important trophic link between seagrasses, epiphytes and the carnivorous fauna[68]. In contrast, as much as 99 percent of dugong and 97 percent of adult green turtle diets consist of seagrass[75] with the remainder comprising invertebrates and algae that are usually, though not always, incidental foods[50,116].

Seagrasses may significantly influence the physical, chemical and biological environments in which they grow by acting as 'ecological engineers'[153]. The roles of different seagrass species in their communities vary depending on their stature and life history. The often sparse meadows typical of the GBR are probably less important for sediment trapping than in other regions due to their smaller size[105,70], often being less than 10 cm in height[22,90,56]. Seagrasses can attain high productivity rates comparable to the highest production occurring in terrestrial ecosystems[64,35], although this is mostly based on information from regions other than the GBR. Known leaf growth rates of coastal seagrasses in the GBR range from 0.3 grams dry weight (DW) per metre squared per day for *Syringodium isoetifolium* to 2.0 grams DW per metre squared per day for *Halodule uninervis*[87,139]. These are well below the global average of 3.8 grams DW per metre squared per day[45], but growth rates can increase significantly following intense grazing by dugongs[117,94]. Some GBR seagrass tissues are often less than two percent nitrogen but in some locations attain extremely high nitrogen concentrations of greater than six percent, becoming a dominant nutrient sink in those areas[106]. Seagrass material typically decomposes rapidly and may contribute to a more rapid cycling of nutrients than adjacent habitats such as mangroves[65].

### 8.1.1 Seagrass habitats in the Great Barrier Reef

There is a perception that seagrasses inhabit a limited range of environments within the GBR. Compared with Caribbean ecosystems, the GBR has limited areas of year-round, dense, highly visible seagrass meadows, yet the extensive inter-reef[25] and inshore seagrass beds[81] result in a diverse assemblage of seagrass habitats[21] (Figure 8.3). In an undisturbed state, the different habitats would have been characterised by low nutrient concentrations, with seagrass growth being primarily

nitrogen limited[11,139]. It is also probable that some variation in biomass occurs seasonally in response to summer rainfall, tropical storms and cyclones that result in large flows of sediment-laden fresh water. These have the dual impact of reducing available light (temporarily) and increasing the availability of nutrients. Large grazers, eg dugongs (*Dugong dugon*) and green sea turtles (*Chelonia mydas*) are also an important and unique feature in structuring tropical Australian seagrass communities in the region[21,100].

Variation in morphology, ecology and ecosystem functioning of different species leads to structural and ecological differences among seagrass species and their associated communities[144] (Figure 8.4). Carruthers et al.[21] refined this inherent variability into functional groups for tropical habitats of northeast Australia including the GBR. These authors defined four broad categories of seagrass habitat as 'rivers and inlets', 'coastal', 'reef' and 'deep water'; each has one dominant controlling factor. Coastal and reef habitats are further separated into subtidal and intertidal, and key drivers of structure and function in these communities described[21].

The 12 seagrass species that occur in the GBR represent a range of capacities to respond to differing environmental conditions (Figure 8.4). Short lived, structurally small species such as *Halophila* contrast with robust, long-lived, structurally large species such as *Enhalus acoroides*. Growth form of each species has consequences for their recovery strategies and adaptability to disturbances. The smaller,

***Figure 8.3*** *Seagrass habitats of the GBR. Dominant seagrass species associated with each habitat are indicated*

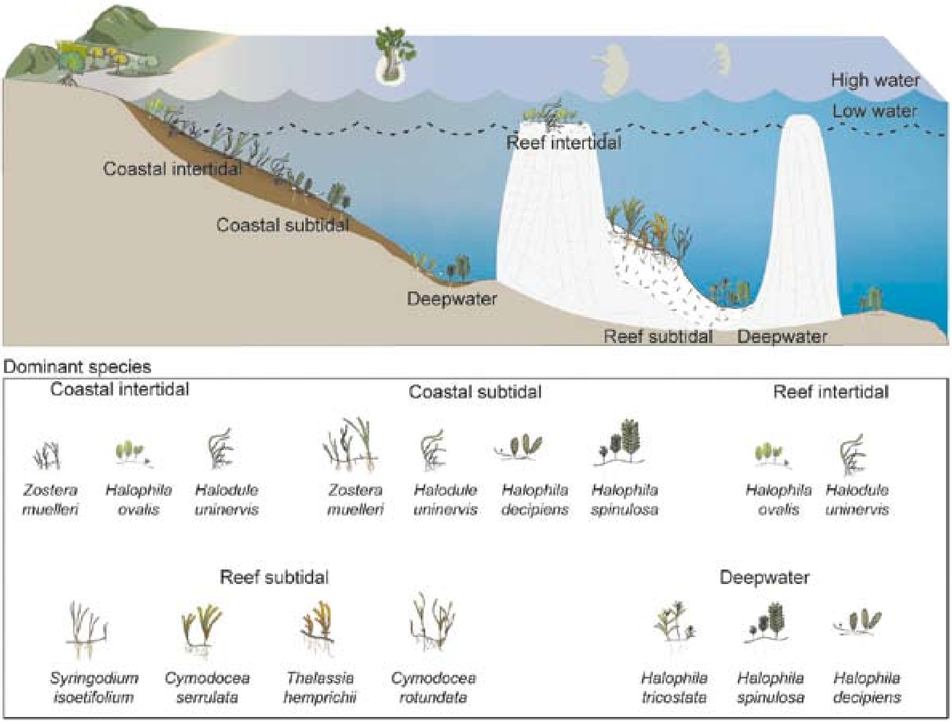
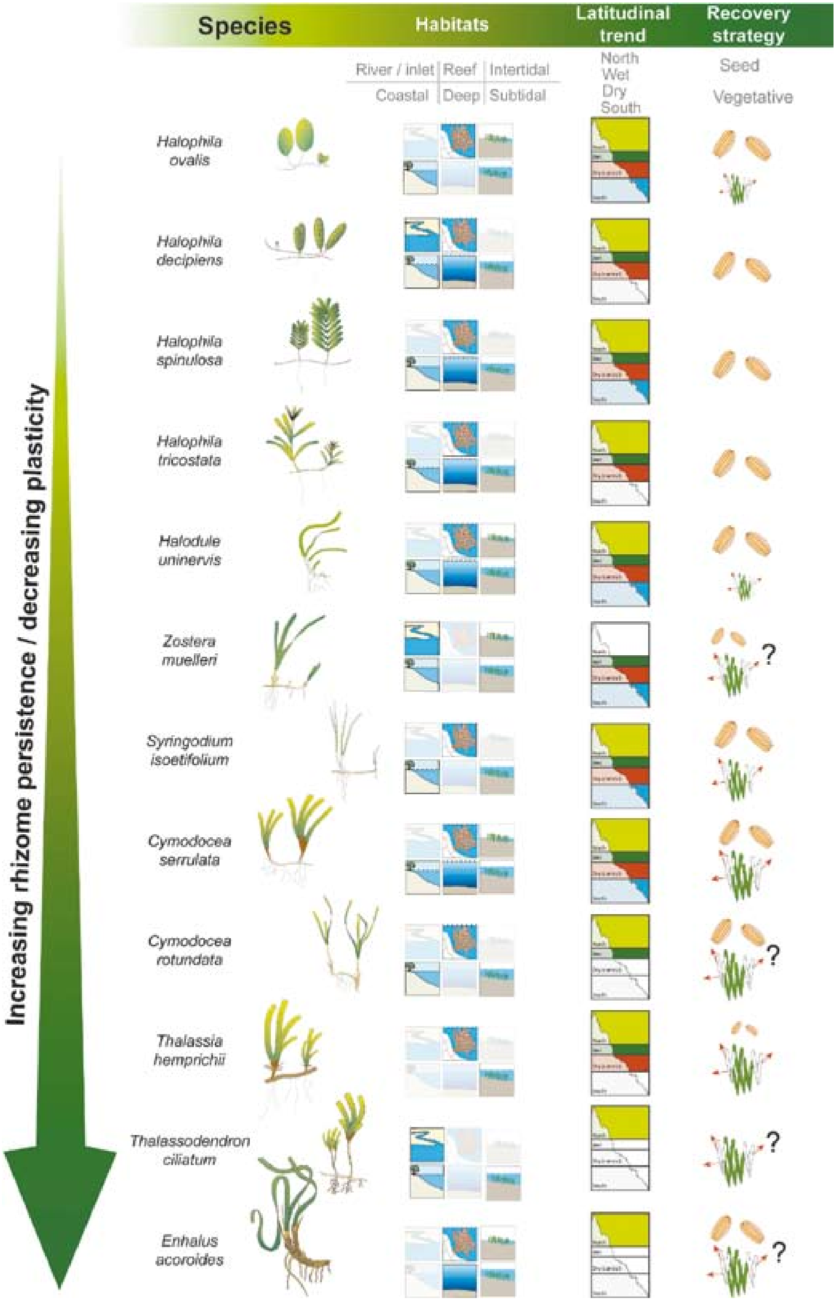


***Figure 8.4*** *Seagrasses of the GBR, arranged from top to bottom in order of structural size, rhizome persistence and reverse order of morphological plasticity. Habitats and regions where they occur commonly within the GBR region, and their main mechanism of recovery to disturbance are shown using icons named at the top of each column*



faster-growing species may respond to changing conditions more rapidly, and as a result are already dominant in highly disturbed ecosystems such as intertidal and heavily grazed habitats. In contrast, the more persistent species, such as *Enhalus* and *Thalassia*, may take a longer period to be impacted due to enhanced resistance in the short-term but in the longer-term have limited capacity to recover.

## 8.1.2 Critical factors for seagrass survival

Seagrasses require light, nutrients, carbon dioxide, substrate for anchoring and tolerable salinity, temperature and pH to survive; limitations to these basic requirements result in seagrass loss and lead to declines in ecosystem services. Different seagrasses vary in their specific requirements for these resources reflecting diversity in growth strategies, resource utilisation requirements and as a result adaptability, all of which are important determinants of community composition.

### *8.1.2.1 Light*

Light availability dictates the depth to which seagrasses may grow. Species with the ability to survive on lower levels of incident light, mostly from the genus *Halophila*[147], are those found in deeper water and highly turbid waters. However, as seagrasses generally have high minimum light requirements compared to other marine primary producers, they are particularly sensitive to low light availability[40]. There are numerous cases of seagrass loss associated with the reduction of light, some of the most dramatic examples occurring in Australia[17,54,143,40,132,120].

Light-related seagrass loss can follow several cause-effect pathways. For example, meadow loss can be triggered by rapid and ongoing increases in available nutrients promoting the development of algal growth in the water column or epiphytic algae growing on seagrasses[40]. Both types of algal bloom reduce the amount of light reaching the seagrass plants[17,18,132]. To date, this is a phenomenon more commonly observed in temperate environments.

A phenomenon more common in tropical regions is the ongoing introduction or resuspension of sediments and other particles into the water column, which leads to increased turbidity and reduced light availability[143,118,87]. Experimental assessments of seagrass tolerance to reductions in light availability have revealed species-specific relationships. Structurally small, higher turnover *Halophila* species, common throughout the GBR and Australia-wide in dynamic habitats such as estuaries[147], die rapidly under complete shading after approximately 40 days[88]. In contrast, structurally large seagrasses such as *Posidonia* species (temperate) can survive for extended periods (more than 140 days of shading)[54,32].

### *8.1.2.2 Nutrients*

Seagrass productivity is often nutrient limited or co-limited[45]. As a result, increases in nutrient availability may increase seagrass growth. This has been observed in the GBR[138,102]. For example, the expansion of seagrass meadows around Green Island off Cairns since the 1970s is associated with an increase in nutrient availability and may be a consequence of increased nutrient delivery to the GBR lagoon[139]. While elevated nutrients may enhance seagrass growth, they can also stimulate algal blooms resulting in light limitation[132,120], although stated previously, this has not been observed in the GBR. At present, the relationship between seagrass growth and nutrient availability in the GBR appears to be that of nutrient limitation in outer reef locations to the point where seagrasses are often absent. However, coastal regions along the GBR have significant terrestrial sediment inputs and seagrasses appear to be only secondarily limited by nutrients, although experimental evidence does indicate enhanced growth under enhanced nutrient concentrations[138,102].

To date no observation of a direct impact of nutrients causing seagrass decline in the GBR has been reported[127]. However, in north-eastern Australia nutrient input rates are often associated with the mobilisation of terrestrial sediments and their subsequent runoff. Based on this, Abal and Dennison[1] predicted that detectable nutrient-related impacts on seagrass meadows might result from higher sediment loads associated with river flood events. This is supported by research on seagrasses in subtropical Moreton Bay that found tissue nutrient content of seagrass close to river mouths were higher than those more distant[138]. These observations suggest that nutrient inputs do influence seagrasses in the GBR, although nutrients *per se* have not been the cause of any declines observed to date.

### 8.1.2.3 Physical disturbance

Disturbance regimes are particularly important to local seagrass meadow survival and community composition. In tropical Australia grazing by dugongs, which are obligate seagrass feeders, controls the species within a community when grazing pressure is high[117,94]. Sediment movement and fresh water due to flooding during storm and cyclonic events are also known to affect seagrass communities[118,19]. The resilience of seagrass communities to these events will vary greatly depending on community type. For example, species that are structurally smaller and rapidly growing are typically adapted to higher disturbance regimes (eg *Halophila* and *Halodule*), or higher energy environments on rocky substrates (eg *Thalassodendron*)[144]. In contrast, species which occur in lower disturbance environments such as sheltered bays and estuaries are higher biomass, slower colonising seagrasses such as *Thalassia* species. Disturbance can also affect seed bank reserves and long-term adaptability of seagrasses[118,67,148].

### 8.1.2.4 Salinity, temperature, $CO_2$ and pH

Typically, seagrasses grow best in salinities of 35 parts per thousand, although they have been observed in salinities from 4 to 65 parts per thousand[62]. It is clear that some seagrasses are more tolerant of wide fluctuations in salinity with the widespread seagrass *Halophila ovalis* being among the most tolerant[38]. Temperature is a critical factor in plant survival, and in the marine environment, also controls the range of pH and dissolved carbon dioxide ($CO_2$) concentrations in the water column. Temperature-pH-carbon concentration optimums in seagrass are species-specific and partially constrain the current spatial distribution that represents the long-term histories of species[5]. In addition to affecting water column chemical composition, temperature influences the rate of growth and the health of organisms, particularly at the extremes. In the GBR, temperature tolerance experiments suggest upper temperature limits to seagrass survival in this region[20]. Limited research has been conducted into the specific responses of seagrasses to the potential influence of environmental parameters that may affect plant physiological status under climate change impacts[131].

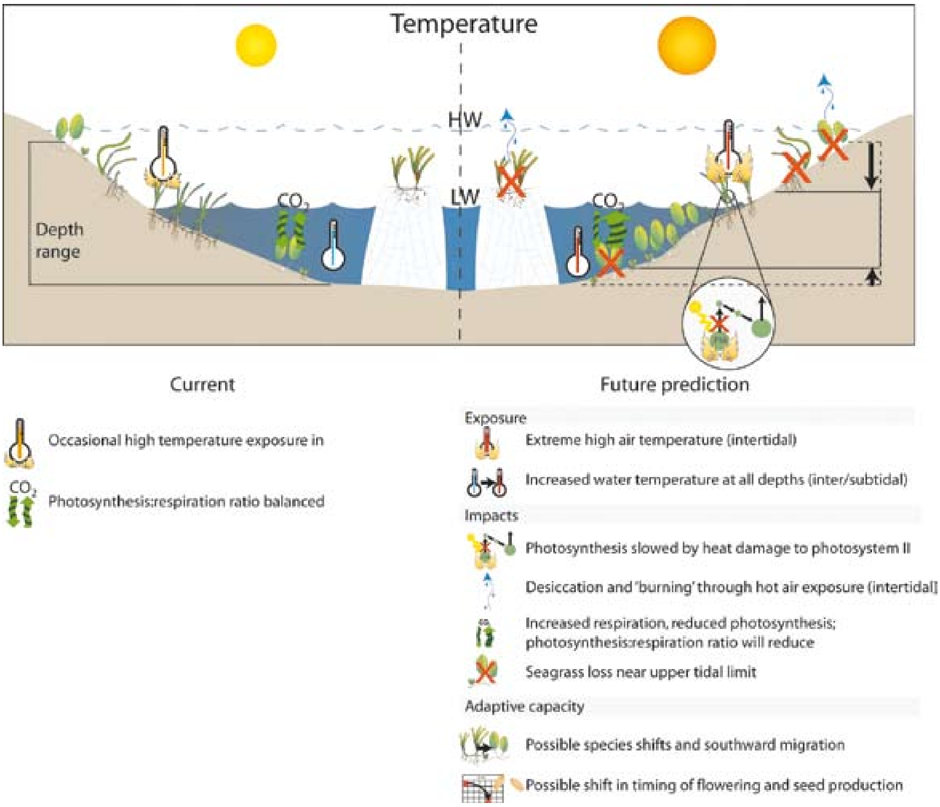
## 8.2 Vulnerability of seagrasses to climate change

Different species and habitats will vary in their tolerances to climate change and these have been considered in this assessment of their vulnerability. We categorise seagrass community responses to climate change as either changes to seagrass community structure or abundance. Based on the scenarios outlined in this volume, we predict that the greatest impact of climate change on seagrasses will be caused by increases in temperature, particularly in shallower habitats where seagrasses are present. In turn, sea level rise, disturbance regimes, flooding and the other changes will limit the survival capacity of seagrasses throughout the GBR.

### 8.2.1 Changes in air and sea surface temperature

Current sea surface temperatures in the Great Barrier Reef are warmer than they have been over at least the past 250 years (Lough chapter 2). Climate change scenarios suggest elevated temperature extreme ranges are projected to rise between 1.2°C and 4.1°C by 2100. Within this framework, the impacts of increasing temperature on seagrasses will be particularly significant for coastal intertidal and shallow subtidal seagrasses (Figure 8.5).

***Figure 8.5*** *Expected impacts of increased sea surface and air temperature on seagrasses based on climate change predictions for the GBR*



### 8.2.1.1 Exposure – temperature

All seagrass habitats will be affected by elevated sea temperatures. In the relatively shallow waters of the GBR lagoon, the northerly flowing coastal current mixes down to approximately 20 metres, due to persistent south-easterly trade winds[53]. As there is currently no evidence of a persistent thermocline across the GBR lagoon, it can be assumed than in waters shallower than 20 metres, temperature at depth will reflect surface temperature. Seagrass in deeper waters, ie greater than 20 metres, would be impacted to a lesser extent from short-term changes in air and sea temperature due to the buffering effect of water depth.

Intertidal habitats will be the most severely impacted by increases in air temperature as exposure and desiccation are significant factors limiting the upper distributional limits of seagrass meadows. In shallow pools seagrasses are exposed to desiccation during low tidal periods due to exposure to air, high incident solar radiation and increased salinities due to higher evaporation rates[37,47].

### 8.2.1.2 Sensitivity – temperature

Water temperature is a major factor controlling seagrass photosynthesis and elevated temperatures generally increase photosynthesis in tropical species over a wide range of temperatures[110,133]. The thermal tolerance of seagrasses depends on the individual species and their optimum temperature for photosynthesis, respiration and growth. Generalisations on the sensitivity of photosynthesis to temperature increases can be drawn from terrestrial plants. As temperatures increase (up to an estimated 38°C based on land plants) the rate of photorespiration increases reducing the efficiency of photosynthesis at a given $CO_2$ concentration. The cause of thermal stress at higher but moderate temperatures (38 to 42°C) is the disruption of electron transport activity via inactivation of the oxygen producing enzymes of photosystem II[126]. Above these temperatures many proteins are simply destroyed in most plants.

Experimental studies on tropical seagrasses demonstrated that the sensitivity of photosynthesis is species specific as *Cymodocea rotundata*, *Cymodocea serrulata*, *Halodule uninervis* and *Thalassia hemprichii* are more tolerant to short term (1 to 4 hour) exposures of thermal stress (35 to 45°C) than *Halophila ovalis*, *Zostera muelleri* (syn. *capricorni*) and *Syringodium isoetifolium*[20]. Where mean sea surface temperature increases up to 2°C we predict a significant impact on species of seagrass that survive at the upper limit of their thermal tolerance[119]. Fong and Harwell[52] suggested that the productivity of tropical seagrass species starts to decline above 30°C. Thorhaug et al.[134] reported that at temperatures elevated 3 to 4°C above ambient, *Thalassia testudinum* showed evidence of reduced standing crop and productivity, and that tropical plants were more tolerant than subtropical plants to elevated temperature. However, some species (eg *Halophila ovalis*) with a wide geographical range have a broad temperature tolerance[119]. However, tolerance of tropical seagrass species to sustained periods of high temperature exposure is largely unstudied.

The sensitivity of seagrass to elevated temperature will also be related to their ability to cope with other impacts. For example, light requirements for carbon production are greater at higher temperatures because of increased compensation irradiance (eg Bulthuis[16]). So species that can tolerate a wider range of light levels, in particular lower levels, would be less sensitive to the impact of increasing temperature on productivity. In addition, as water temperature increases the solubility of gases such as $CO_2$ decreases, a disadvantage for species that are dependent on $CO_2$, although this may be offset

by decreasing pH associated with elevated absorbed $CO_2$ concentrations. Other plant growth factors subject to temperature regulation, including enzyme-mediated processes such as nutrient uptake, are expected to differ between species but remain unstudied.

### *8.2.1.3 Impacts – temperature*

The main impact of elevated sea temperature on seagrasses will be the change in growth rates and general physiological processes of the plants themselves (Figure 8.5). Seawater temperature directly affects seagrass metabolism and the maintenance of a positive carbon balance described above[51,16,155]. These factors influence the seasonal and geographic patterns of species abundance and distribution[17,63,97,119]. At a broad scale, the distribution of seagrass species in the GBR is expected to shift south. For example, species more prevalent in tropical and equatorial waters north of the GBR (eg *Enhalus acoroides* and *Thalassodendron ciliatum*) could expand south. The scale and rate of such change is uncertain as water currents and delivery of suitable recruits via seeds, plant fragments, and other propagules is an important determinant.

Elevated temperatures may also influence the growth of deep water seagrasses although the mechanism and scale of impact is unknown. *Halophila ovalis* has a broad water temperature tolerance and deep water (greater than 15 metres) plants have been found adjacent to submarine hot springs (28.6°C) in the northern hemisphere[73]. Although localised adaptations acquired over evolutionary time scales, exposure to these conditions may explain the wide tolerances observed. The presence of *Halophila tricostata*, an ephemeral deep water seagrass endemic to Queensland, correlates with warmer sea temperatures possibly due to the requirement for greater than 26°C water temperature to affect germination[72]. *Halophila tricostata* may have a broader distribution with increasing water temperatures.

High air and water temperatures and desiccation through direct exposure to air are probably the most important factors limiting upper intertidal distribution of seagrasses. Recent *in situ* monitoring of tropical intertidal seagrass canopy seawater temperatures[a] reported seagrass 'burning' when temperatures up to 10°C above the seasonal average occurred, especially during low spring tides and midday solar exposure[20]. During these events seagrasses may be exposed to elevated seawater temperatures for periods of 3 to 4 hours. High seawater temperatures and desiccation have negatively affected seagrass meadows in a number of areas worldwide[142,49] with one episode of temperature-related seagrass loss linked to an El Niño event[129].

Intertidal seagrass communities (both coastal and reef) are exposed to a certain level of desiccation during tidal cycles. Typically, desiccation risk will limit the extent of seagrass in the upper intertidal[10]. Periodic leaf burn-off can be associated with the changing lunar cycle which results in different timing of tides. Exposure during the middle of the day in full sun is more damaging than exposure during the middle of the night. As the expected increases in sea and air temperatures occur, so will the frequency of desiccation events due to the higher intensity of exposure. Such an increase in frequency of desiccation events is expected to favour a species composition dominated by *Halodule/Halophila* due to their faster recovery times and smaller stature limiting their exposure during low tide.

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[a] www.seagrasswatch.org

Increased temperature may also alter seagrass distribution and abundance through direct effects on flowering[96,48] and seed germination[58,111]. Temperature plays an important role in flower development, flowering induction and controlling the flowering process[2]. For example, the initiation of flowering in *Zostera* is related to a rapid rise in ambient temperature, from the annual low, and associated increase in day length[89]. Similarly, anthesis (the opening of flowers) has been observed in southern Queensland during late spring/early summer before temperatures reach their summer peak[34,90,122].

The impact of elevated temperature on seagrass sexual reproduction and flowering is unclear. Some species may increase the duration of their flowering period, while for other species the initiation of flowering may be altered. *Halophila ovalis*, possibly the most ubiquitous seagrass species in the GBR, flowers throughout the year with ambient temperature between 15 and 27°C (peak flowering 23 to 26°C in Moreton Bay)[94]. Changes in temperature may have a negligible effect on this unusually tolerant species. However, the environmental factors that initiate sexual reproduction remain unexplored, and for most species, changes in temperature are expected to exert a significant effect on flowering.

#### *8.2.1.4 Adaptive capacity – temperature*

Seagrasses that persist in coastal and reef intertidal habitats of the GBR are adapted to a wide range of environmental extremes. Seagrass communities that dominate along the northern intertidal coastal fringe of the GBR, are generally comprised of species that are adapted to tolerating extremes in temperature (eg *Halodule uninervis* and *Thalassia hemprichii*), or alternatively have the ability to recolonise after an extreme event (eg *Halophila ovalis*). This is in contrast to communities that dominate the southern intertidal coastal fringe of the GBR, which are generally composed of more persistent and stable species such as *Zostera muelleri* and it is unlikely that species such as these will be able to successfully adapt. Elevated sea surface and air temperature are likely to cause intertidal seagrass communities to contract – the shallow edge will move seaward due to desiccation and elevated temperatures.

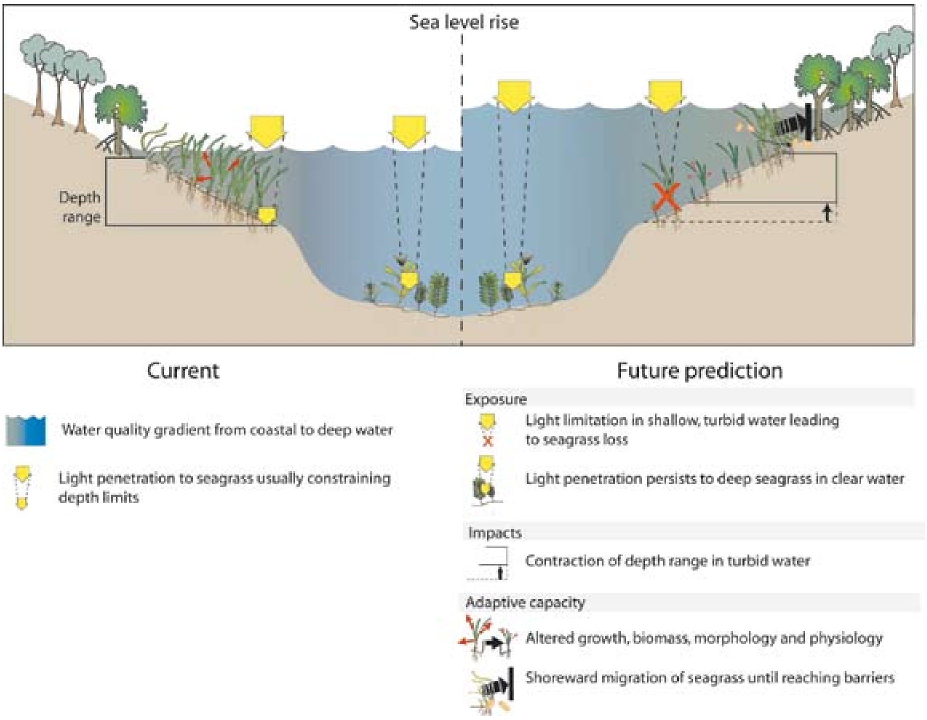
#### *8.2.1.5 Vulnerability and thresholds – temperature*

The vulnerability of seagrasses to elevated air and sea temperature will be species dependent, and in some cases may be significant. At present the inherent variability of seagrasses responses to changing temperature *in situ* is virtually unmeasured (cf. Thorhaug et al.[134]) making the identification of thresholds vague. However, it is expected an elevated temperature of 5°C, even if experienced for just a few hours during low tide, will result in significant loss of seagrass in shallow or intertidal seagrass meadows. Vulnerability may be further exacerbated by other indirect temperature associated impacts such as increased algal epiphyte growth and the intensity of extreme weather events, which will be discussed in following sections.

### 8.2.2 Sea level rise and coastal inundation

Seagrass distribution is usually limited by light penetration. Sea level is predicted to rise between 10 and 90 centimetres within the next century. This increased water depth will further attenuate light penetration to seagrass (Figure 8.6). The process of sea level rise will have an additional impact of inundating massive tracts of coastal land. The degree to which the coastline is regressed will depend

***Figure 8.6*** *Expected impacts on seagrasses from sea level rise based on climate change predictions for the GBR*



upon the local topography, however as a rule of thumb it has been estimated to be up to ten times the vertical change in sea level, so it is possible to have 10 metres horizontal inundation of the coastal zone[15]. Regression of the coastline will cause erosion of shallow sediments[44] impacting seagrass habitat availability. The hardening of shorelines through coastal development poses a significant risk to seagrass habitat availability as sea levels rise.

### *8.2.2.1 Exposure – sea level rise*

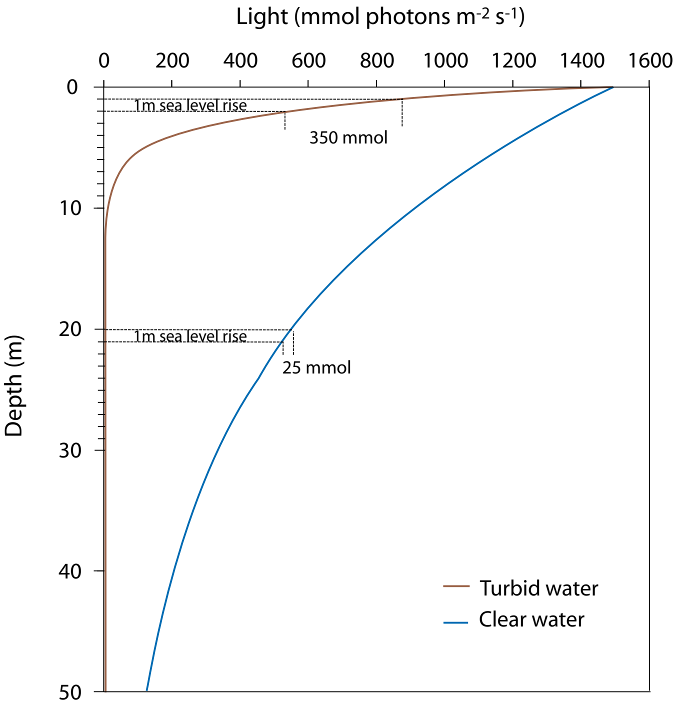
All seagrasses within the GBR will be exposed to changes in sea level and therefore a reduction of light penetration and habitat availability. Topography of the land adjacent to the current shoreline will define the degree of horizontal inundation. The region south of Cooktown has the largest surface area of land one metre above sea level predominantly within river floodplains, while in the northern GBR there will be less inundated land. Inundated areas will be potentially habitable for seagrasses. Furthermore, the lower distribution of current intertidal seagrass meadows will become subtidal and a change in seagrass community composition will follow. One note of caution to this interpretation is that while inundated lands may occur, where substantive mangrove communities, rocky shorelines and coastal developments that create hard surfaces, such as concrete, exist the capacity of seagrasses to colonise will be curtailed.

### 8.2.2.2 Sensitivity – sea level rise

The sensitivity of seagrasses in the GBR to light reduction from sea level rise is likely to depend on local water quality conditions and the species present. Seagrass depth limits are usually constrained by light availability with the deepest meadows growing at their minimum light requirements[40]. Seagrasses growing at their depth limit will be the most sensitive to sea level rise as increasing water depth reduces light penetration. Assuming minimum light requirements are known for each species of seagrass it would be possible to estimate the spatial extent of impacts of light reduction.

Estimation of impacts of sea level rise also requires knowledge of the light attenuation coefficient, which describes the exponential reduction of light with depth, of clean mid-reef water versus turbid coastal water throughout the GBR. Without this information, it is anticipated that deep seagrasses inhabiting clean water will not be impacted, but those in shallow, highly turbid waters will be heavily impacted. This is due to the small relative change in light availability with depth for the deep water regions, while in shallow, turbid water a small change in depth results in a large change in total light penetration (Figure 8.7). Seagrasses vary in their tolerance to long-term reductions in light availability; *Halophila* species often inhabit a range of high- to low-light regions while *Thalassia* and *Cymodocea* species are often found only in high-light habitats and may be more sensitive to light reductions[21].

***Figure 8.7*** *Depiction of the impact of light availability with depth to seagrasses for different light penetrations based on a one metre sea level rise*



### *8.2.2.3 Impacts – sea level rise*

There is no experimental data on the impact of sea level rise on seagrass distribution[44]. There has been no documented evidence of seagrass loss due to sea level rise and there have been no experimental manipulations to suggest how rapidly seagrasses could adapt to these conditions. The greatest impact will occur on the deep coastal edge of the meadows where, currently, light availability only just meets minimum light requirements[1] but with elevated sea levels will become limiting to growth. This could result in complete loss of seagrasses at the deeper edge, while for the remainder of the meadow, biomass and growth are likely to reduce as these are known to reduce with increasing depth for many seagrasses[21].

Seagrasses could colonise newly inundated lands; however, inappropriate coastal sediments, rocky shores or other barriers will limit the capacity of seagrasses to colonise. The simplest outcome would be for the meadow to migrate up slope the same distance that the lower edge was lost (no net loss of seagrass habitat or biomass) however we do not believe this is likely in many cases. Species with rapid recruitment capabilities (eg *Halophila, Halodule, Zostera*), however, will occupy new areas more rapidly than slower recruiting species (eg *Thalassia, Cymodocea*)[100,149] and other environmental drivers are likely to influence community composition such as substrate type. Duarte[44] suggested that increased sea level would result in uprooting of seagrass due to shoreline erosion of newly inundated but unstable (and unsuitable) sediments. These losses may be further exacerbated during storm events. The implications of this physical disturbance regime are addressed in section 8.2.3.

### *8.2.2.4 Adaptive capacity – sea level rise*

All seagrasses are capable of responding to light reductions by altering their physiological capacity and morphological structure. However, at the depth limit, the meadows are already at the extreme edge of their light tolerance range and are unlikely to adapt to further light reductions. For shallower seagrasses some response to reduced light availability is certain. This is likely to include reduced growth and biomass but may also include some physiological responses, such as changing carbohydrate utilisation and pigment concentration, or even a change in morphology[87,148] (Figure 8.6).

Seagrasses are well adapted to growing both vertically and horizontally. Given this, seagrasses should be capable of growing up slope as sea level rises. The potential rate of vertical growth of most seagrasses will be greater than the predicted rate of sea level rise. Being flowering plants, seagrasses are also capable of seed production and dispersal. Tropical species typical of the GBR are particularly reliant on sexual reproduction strategies[67]. Intertidal regions are currently inhabited predominantly by *Halophila ovalis, Halodule uninervis* and *Zostera muelleri*. All of these species have been known to rapidly colonise newly available substrate, usually following disturbance[67,19,123,94].

The sediment type of newly inundated shoreward regions will influence the capacity of species to colonise. Amongst the sediment characteristics likely to influence suitability for seagrasses are nutrient status, particle size and redox potential. Physical obstructions to shoreward migration may force an overall contraction of the meadow. In built-up areas where structural features such as rock walls or groynes are in place, shoreward migration will be inhibited. The interaction of seagrasses with other habitats is less well known. For example, it is speculated that sediment accretion within mangroves will enable their current seaward margin to persist (Lovelock and Ellison chapter 9) and this may prevent habitation of these areas by seagrasses. If inundation penetrates into cane fields this will encroach into substantial areas in the wet tropics region of the GBR. Another often-overlooked aspect of coastal inundation is the addition of nutrients to the marine environment as much of the low-lying land is coastal alluvial flats that have been utilised for agriculture for many years. It is unknown what the scale and impact of these additions may be to coastal marine ecosystems under these altered conditions.

### 8.2.2.5 Vulnerability and thresholds – sea level rise

Estimating thresholds for complex interactions between light and sea level rise is difficult given that we are only aware of the minimum light requirements for one tropical seagrass species (*Zostera muelleri*). Before estimates can be made, a better understanding of the variation in tropical species light requirements is needed. However, it is certain that some seagrass will be lost near their lower depth limits in turbid coastal waters. The shoreward migration of seagrasses in response to newly inundated areas will probably be at least partially blocked by physical obstructions. Whether this results in an overall gain or loss of seagrass will depend on a number of factors including the relative area of habitat lost at the depth limit versus that gained (potentially a wide margin in some areas) and the suitability of new areas for colonisation. We suggest some 3000 km$^2$ of potential habitat will become available for seagrasses in the GBR under a one metre sea level rise (NB this is currently an overestimate for 2100 by climate change models). However, we do not know the extent of deep-edge seagrass loss or shallow-edge competition with mangroves and other hard substrates. Modelling of the relative depth limit changes would be required once a greater understanding of species-specific light limitation are available.

## 8.2.3 Physical disturbance – tropical cyclones and major storms

Less frequent tropical cyclones and major storms are predicted in the next 100 years; however, the number of events in the central and southern GBR may increase. In contrast, the intensity of cyclones and major storms is likely to increase, resulting in events with stronger winds, greater turbulent water motion, lower atmospheric pressure, greater storm surge and greater rainfall. The frequency and intensity of cyclones and major storms is also linked to the El Niño Southern Oscillation (ENSO) cycle, so any changes with this cycle will affect the frequency and intensity of cyclones and major storms.

### 8.2.3.1 Exposure – physical disturbance

There are four main threats from storms and cyclones that result in physical disturbance: sediment movement (erosion and deposition), turbulent water motion and storm surge. Tropical cyclones and major storms are likely to cause sediment movement within seagrass habitats due to strong winds, creating turbulent water motion. Sediment movement will impact seagrasses through erosion or depositional processes. Compounding these impacts, low atmospheric pressure cyclones and storms may create storm surge and turbulent water motion that will also cause sediment movement[125] and dislodge seagrass.

All seagrass regions in the GBR are likely to be affected by physical disturbance from cyclones and major storms. However, deep water habitats are unlikely to suffer physical disturbance as they are more protected due to the dissipation of energy with water depth[118].

### *8.2.3.2 Sensitivity – physical disturbance*

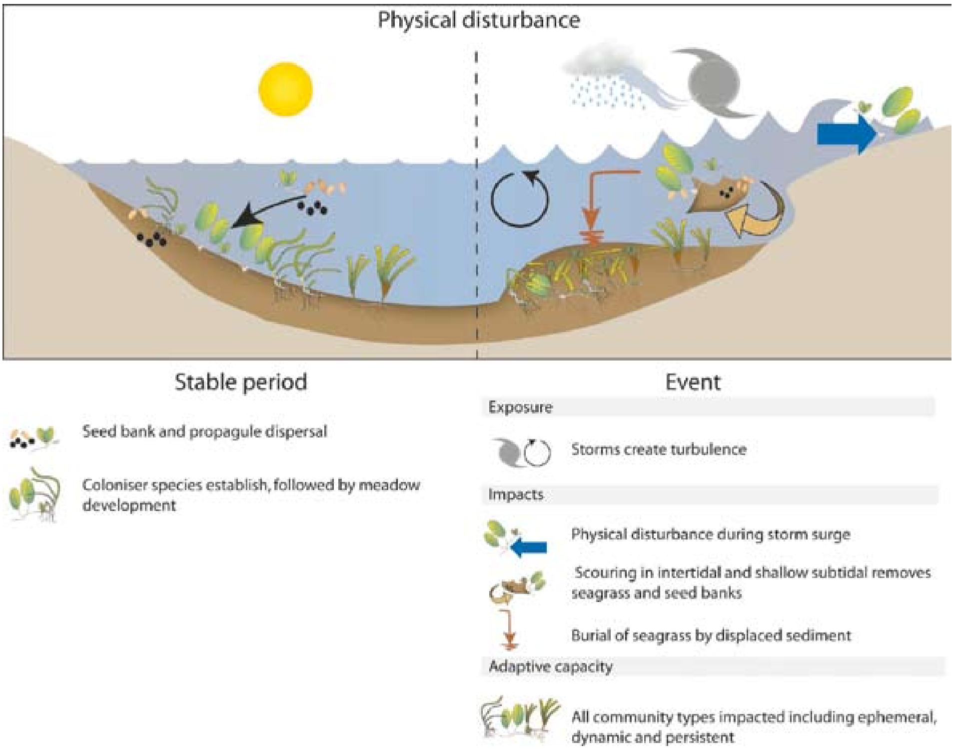
The sensitivity of seagrasses to physical disturbance from cyclone and flood events is dependent on the strength of the wind, energy of the turbulent water motion (sheer stress), atmospheric pressure, storm surge height, direction of cyclone and storm movement and tide position during the event. The location of seagrass, especially depth, will influence their sensitivity. Intertidal and shallow subtidal meadows will be more sensitive due to the greater energy at these shallower depths. Thus the tide height at the time a cyclone or storm passes may determine the area that is impacted. Although deeper habitats (greater than 10 metres) are less sensitive, in some cases seagrass habitats at depths of 23 metres have almost been completely removed by tropical storms in the Caribbean[150].

There is spatial variability in the impact of a cyclone or storm. In some events a meadow may be removed but adjacent meadows remain intact[113]. Similarly, some cyclones may have no impact on the seagrass meadows while others may completely remove meadows[112]. The cause of this variability in meadow response to such disturbances is unknown.

### *8.2.3.3 Impacts – physical disturbance*

The high energy generated from cyclones or storms in Queensland have caused localised sediment movement, and removal of plants[112,113,19], whole meadows[8,113,118,19] and seed banks[114] (Figure 8.8).

***Figure 8.8*** *Expected disturbance cycle impacts based on climate change predictions for the GBR*



Areas up to 1000 km$^2$ have been impacted from a single cyclone event[118], though this event included the additive impact of turbidity from flood plumes. Of the four potential physical disturbance threats, the mechanism that will cause the greatest impact from a cyclone or storm event is not known.

### *8.2.3.4 Adaptive capacity – physical disturbance*

In all documented cases of seagrass loss from cyclones and storms in Queensland, there has been recovery[8,113,118,19]. Recolonisation of seagrass to completely denuded areas can take from months to years[113,118,19]. The time to return to the pre-disturbance cover, biomass, or species composition may take from one to ten years after the initial disturbance[8]. When all seagrass plant material (shoots and rhizomes) in the meadow is lost, recovery has been documented via seeds[19]. Dispersal of seeds between meadows has been inferred from population genetic studies and is likely to be an important mechanism for meadow recovery when large-scale disturbance removes entire meadows[94] (Figure 8.8).

Seagrass communities have been defined in this chapter based on their persistence. Species growing in ephemeral and dynamic communities (eg *Halophila* spp., *Halodule uninervis, Syringodium isoetifolium* and *Zostera muelleri*) are better adapted to live in disturbed environments. Therefore, these species are likely to recover faster than other later successional species such as *Cymodocea* spp., *Thalassodendron ciliatum, Thalassia hemprichii,* and *Enhalus acoroides*[8,144]. If the time between successive cyclone and storm disturbance events is not long enough for slower recruiting species to recover, then there may be a shift in species composition in areas that have repeated high intensity disturbance events.

### *8.2.3.5 Vulnerability and thresholds – physical disturbance*

Due to the ability of tropical seagrasses to recover from physical disturbance associated with cyclones and storms we predict a low vulnerability to this exposure threat. However, this prediction does not include interaction with river flood plumes, which deliver another set of threats due to turbid, fresh water that may carry excessive nutrients and toxicants. It is not possible to present thresholds for seagrass persistence to cyclone and storm events.

There is no information for any seagrass species found in Queensland on the energy (sheer stress) or velocity they can withstand, or the energy required to move sediment that may erode or deposit sediments on seagrass resulting in a negative impact. Intertidal seagrasses have been shown to recover from loss in the GBR within two years, taking up to five years to re-establish fully[19,148]. Recovery from dugong grazing can be very rapid, in the period of months[94]. Coastal reef seagrass habitats near Townsville have been observed to recover over a period of five to ten years following loss due to cyclonic impacts[8]. No data is available to estimate recovery times for other habitats and it is unknown what the impact of meadow loss will be locally or regionally on co-habiting species or those that feed upon them.

## 8.2.4 Rainfall and river flood plumes

Climate change predictions indicate that total rainfall may increase in the southern and northern GBR but may decrease in the central GBR. As a result of changing rainfall patterns, large-scale river flood plumes may occur more often in the central and southern GBR, with no expected change in the northern region. Across all regions flood events are likely to be more extreme, generating plumes

extending further into the GBR lagoon and the impact will be longer lasting. The major impacts of flooding and river flood plumes are expected to be salinity fluctuations (Figure 8.9) and the introduction of sediments (Figure 8.8 for disturbance) and nutrients (Figure 8.10).

### *8.2.4.1 Exposure – rainfall and river flood plumes*

The immediate effects of small-scale rainfall and river flood plumes are that they potentially reduce salinity in shallow water such as intertidal pools (Figure 8.9). Rainfall associated with cyclones and major storms will cause large-scale river flood plumes that influence large areas of habitat in the GBR (Figure 8.11). River plumes transport nutrients, sediment and land sourced toxicants from the catchment to the GBR with larger events generally delivering greater loads[53]. Coastal habitats, both intertidal and subtidal, are, and will continue to be, the most impacted by changes in rainfall and river flood plume activity. Deep water habitats close to river mouths may also be impacted.

Heavy rainfall can directly affect salinity in shallow water such as intertidal pools. A minimum of 11 parts per thousand was recorded in Bolger Bay, Magnetic Island for up to 48 hours during a cyclonic rainfall event (Collins[33] in Birch and Birch[8]). Such a change in salinity is highly likely to have a negative impact on seagrass growth through salinity stress. River flood plumes can be vast – extending for 1000 km along the coast – and can be persistent – lasting for weeks[53]. These low salinity events are likely to impact intertidal seagrass both in coastal and offshore reef habitats (rainfall), and all coastal seagrass habitats (river plumes).

***Figure 8.9*** *Proposed impact of salinity extremes on seagrasses emphasising changes expected under climate change models*

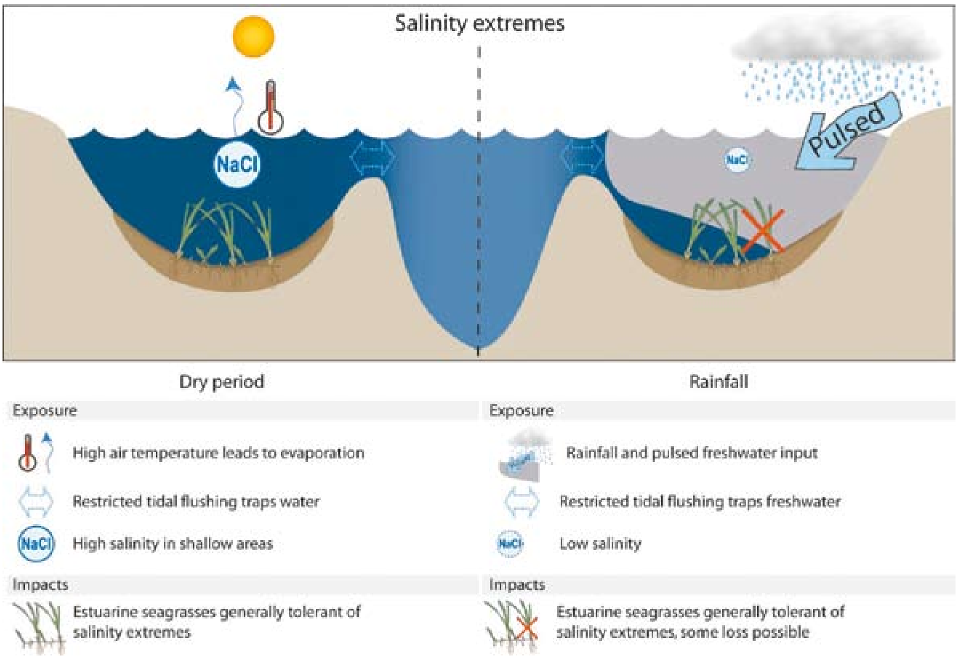
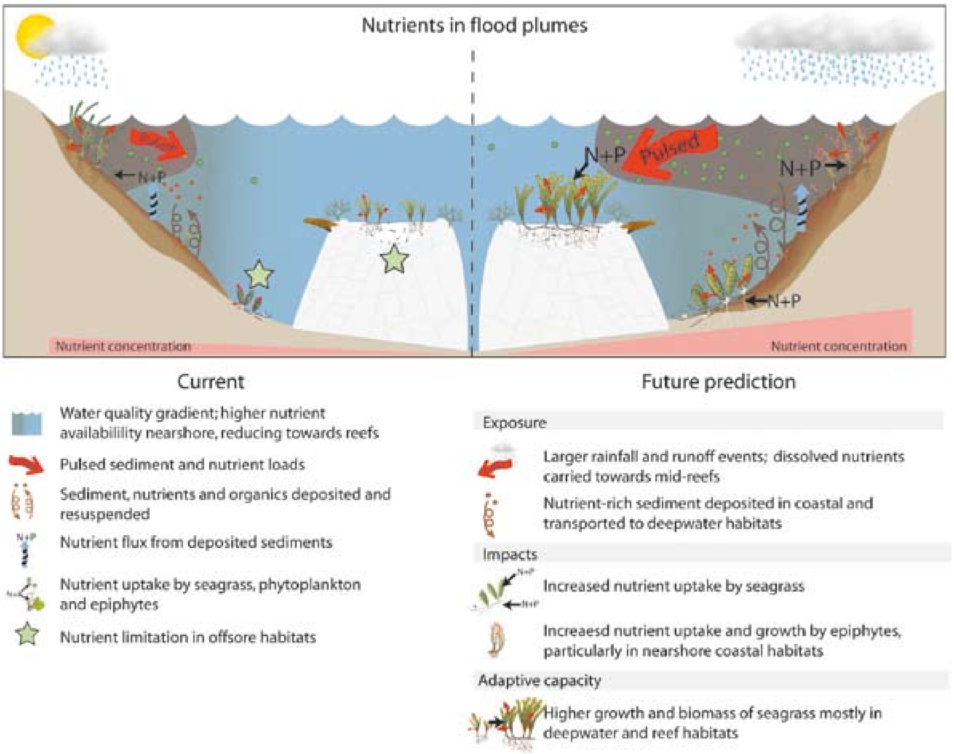


***Figure 8.10*** *Proposed impact of nutrients deposited by flooding on seagrasses emphasising changes expected under climate change models*

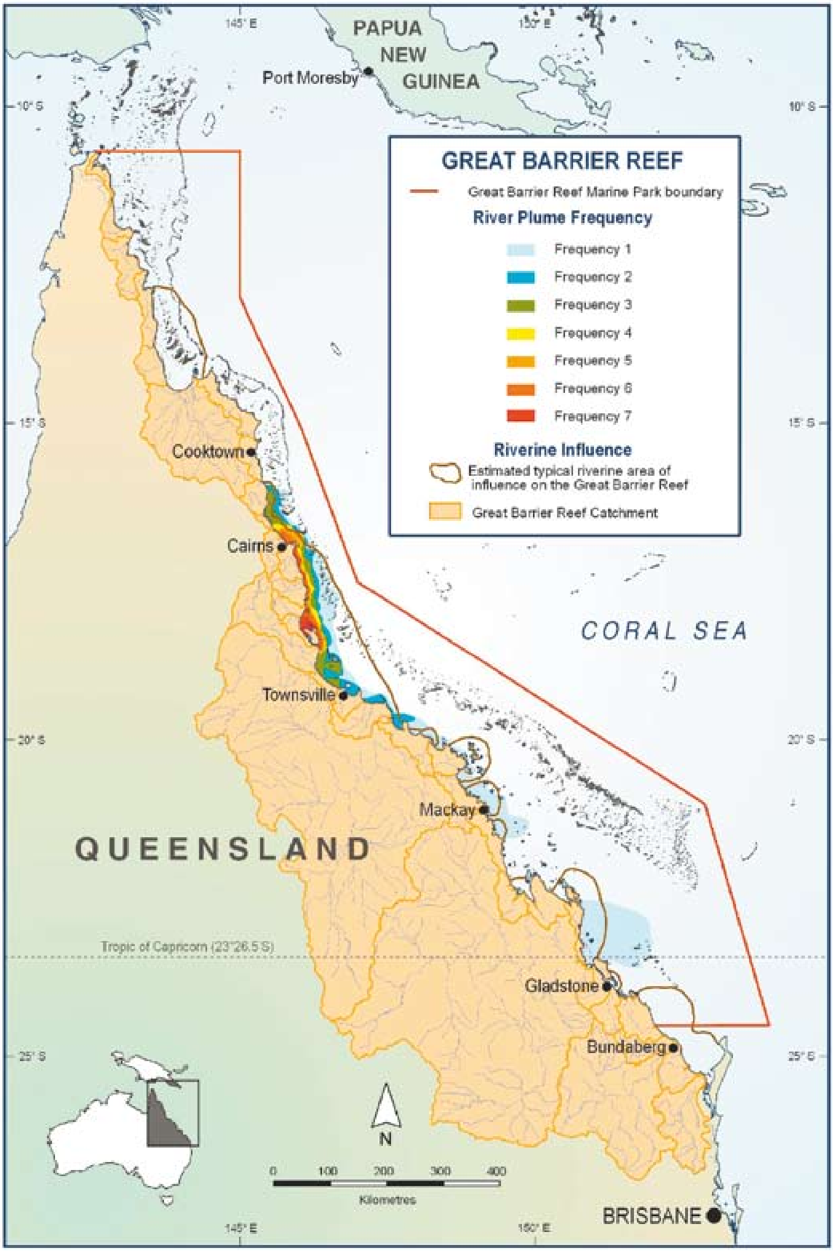


Sediments transported by river flood plumes have an immediate effect on coastal seagrasses through sediment deposition. Smothering of subtidal and intertidal plants occurs as most sediments are deposited within the first few kilometres of a river mouth[76]. In addition, while sediments remain suspended in the water column turbidity is high, and light reaching the seafloor is reduced, impacting coastal and deep water seagrasses that are beneath the plume. River flood plumes can extend 50 km from the coast[41] (Figure 8.11) and last for up to three weeks[118,88]. Sediments also carry nutrients[14] and toxicants[108], thus the concentrations of these associated elements delivered to seagrass meadows will decrease with distance from the river mouth.

### *8.2.4.2 Sensitivity – rainfall and river flood plumes*

If seagrass meadows occur within the spatial extent of either sediment deposition or the flood plume itself, they are likely to be impacted. Seagrasses are sensitive to the deposition of sediments directly on top of them. Where sediment deposition is greater than the ability of the seagrass beneath it to grow through the sediments using energy reserves, plants will die. Anecdotally, seagrass meadows in the GBR are regularly lost due to the deposition of sediments. For example, after flooding of the Bohle River, north of Townsville, intertidal meadows of *Halodule* and *Halophila* were completely covered by sediment (J Mellors and M Waycott, personal observations) and in Sarina Inlet near Mackay seagrass

**Figure 8.11** *Area of influence by flood plumes based on data for the past 80 years in the GBR. Includes river plume frequency during cyclonic events (colour fills indicate the frequency with which a cyclone has generated a flood plume in the region), estimates of riverine influence derived from flood plume and river discharge studies, and modelling results (brown outline)[56]. (Source: C Honchin, Great Barrier Reef Marine Park Authority)*



loss resulted from sediment related smothering (L McKenzie personal observation). No data on the specific sensitivity of seagrasses in the GBR to burial is available although it is intuitive that larger, more robust species such as *Thalassia hemprichii* and *Enhalus acoroides* are more likely to survive than smaller ephemeral species. River flood plumes are also associated with strong currents during their movement from the river out to sea. There is limited information on the strength of currents seagrasses can withstand. A northern hemisphere species, *Zostera marina* can live in habitats with a current speed of up to 1.8 cm per second[69]. This is equivalent to about 3.5 knots, similar to tidal currents in the GBR. At current strengths greater than 4 cm per second (8 knots) the leaves of seagrass are likely to be dislodged by shear forces[70]. It can be assumed therefore that currents greater than 4 cm per second will remove seagrass.

In coastal habitats of the GBR, current evidence suggests light is the main factor limiting seagrass growth[21,86,102,148]. However, in the mid and outer reefs of the GBR, where light is not likely to be limiting due to the absence of terrestrial sourced sediments, nutrients can the dominant limiting factor (Figure 8.11). As such, nutrient enrichment may lead to increases in plant growth and biomass[137,139,102,127] that could result from a greater influence of river flood plumes. Seagrasses are not sensitive to small changes in salinity, and can survive over a large salinity range[64]. As *Halophila ovalis* and *Zostera muelleri* are regularly found growing near river mouths in the GBR it is assumed they can withstand variations in salinity[81]. There are experimental or observational studies on salinity tolerance and exposure that support this for three species found in the GBR, *Halophila ovalis*[64,7], *Halodule uninerivs*[101,64] and *Zostera muelleri*[57,90]. *Halophila* and *Zostera* species can survive in salinities between 10 and 40 parts per thousand, and can survive short-term exposure (approximately two weeks) to salinities less than 10 parts per thousand[64,90,7]. The salinity range for *Halodule* is recorded as low as 3.5 and as high as 62 parts per thousand[101]. Flowering and seed germination of *Zostera* is enhanced in low salinity[34,13,121]. The effect of salinity on other species is unknown.

The extent of sensitivity of seagrasses to a variety of toxicants remains largely unresolved. Based on short-term exposure to herbicides, a few studies have identified water column herbicide concentrations of diuron, atrazine and simazine that impact seagrases (lethal exposure at 100,000 nanograms per litre; or sub-lethal exposure where photosynthesis is impacted at 10,000 nanograms per litre)[60,98]. However, smaller species of seagrass such as *Halophila ovalis* can be impacted by concentrations of diuron as low as 100 nanograms per litre[60]. It is not known what concentration in the sediment impacts seagrasses.

### *8.2.4.3 Impacts – rainfall and river flood plumes*

The impact of rainfall and river flood plumes to seagrass will depend upon the amount of sediment deposited and the persistence of the plume. From a major event in Hervey Bay, just south of the GBR, it was inferred that seagrass loss occurred due to a number of factors such as physical removal, sediment deposition and light reduction[118,88,19]. The importance of smothering by sediments as a contributing factor to this seagrass loss was supported by the observation of up to 10 cm of sediment covering dead rhizomes of *Zostera* at an intertidal meadow in Hervey Bay, Urangan which were lost following the 1999 flood event (L McKenzie, personal observations). No direct evidence of seagrass loss due to lowered salinities or physical scouring due to currents has been reported. However, we can infer a contribution of reduced salinity to seagrass loss during large-scale flood plume events although the scale and nature of the impacts to the seagrass meadow remains obscure. Seagrass loss

due to toxicants has not been observed, although based on herbicide concentrations observed in seagrass meadows following periods of moderate flow[59,95,130], we may assume that loads are greater during high flow events. It is possible that concentrations will reach sub-lethal levels, especially close to river mouths[94]. From limited information on toxicant concentrations in marine waters in the GBR, it appears unlikely that lethal concentrations will be reached.

Where seagrass growth has been limited by availability of nutrients, expansion of seagrass meadows is possible. For example, seagrass meadows have responded to experimental nutrient additions on mid-reef islands of the GBR, such as Green Island[140]. Coupled with observations made through monitoring seagrass meadows at Green Island, the demonstrated increases in meadow extent and density (Queensland Department of Primary Industries and Fisheries, unpublished data) may be related to ongoing increases in nutrients in some mid-shelf reefs. Nutrient rich flood plumes reach Green Island almost every year[42] and it has been inferred that the increase in seagrass biomass is due to nutrient enrichment from these flood plumes.

### *8.2.4.4 Adaptive capacity – rainfall and river flood plumes*

The adaptive capacity of seagrass species to rainfall or flood plumes will partially depend on their capacity to recover from disturbance via seed or vegetative fragments and partially on their initial resistance to the impact. More persistent species (eg see Figure 8.4) should have a higher tolerance for localised impacts, particularly where the impact is moderate and/or short term. There may also be community shifts from more stable communities to more ephemeral communities because of a major event.

### *8.2.4.5 Vulnerability and thresholds – rainfall and river flood plumes*

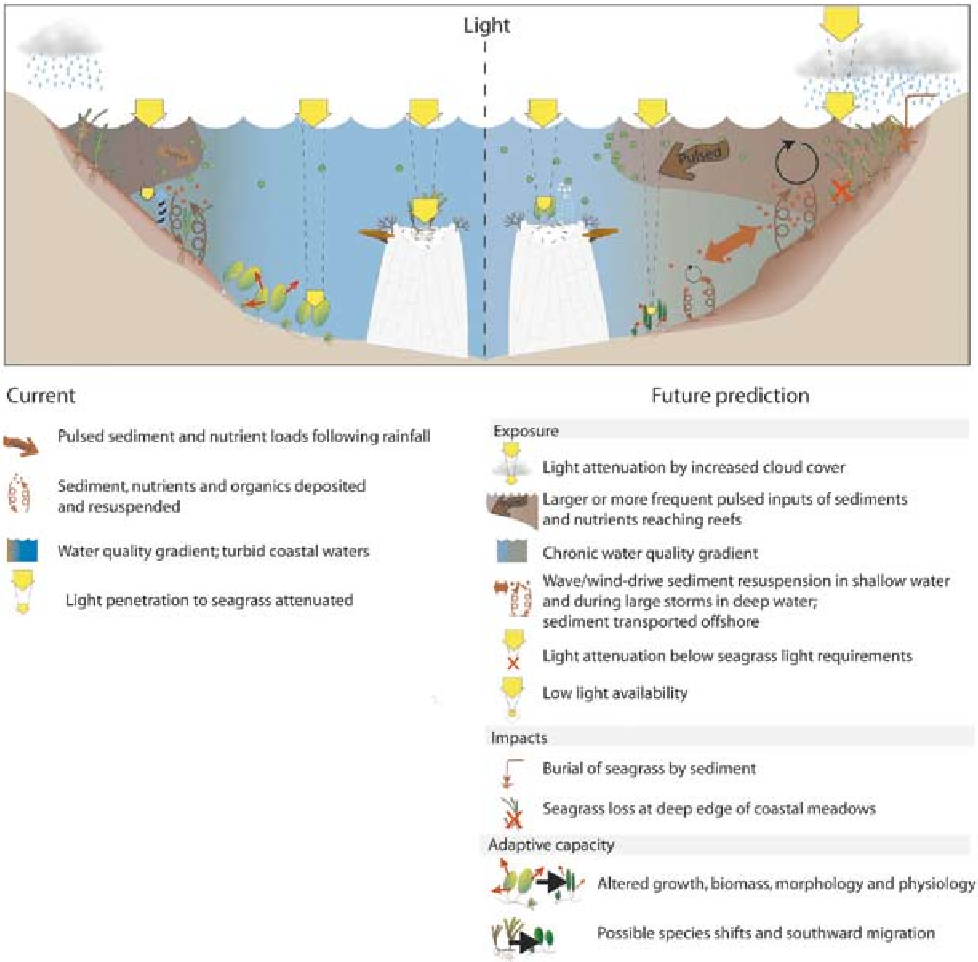
The vulnerability of seagrasses to rainfall and river flood plumes will also vary with community structure. Species growing near river mouths and frequently exposed to these conditions, such as *Halophila, Zostera* and *Halodule*[81], have a low overall vulnerability to this threat. Known thresholds to lowered salinity based on experimental evidence do exist for *Halophila ovalis* (less than 10 parts per thousand for two weeks) but not for other species. Species will be more vulnerable if the growing tissue (meristems) is exposed to low salinity water, particularly those species with areal meristems such as *Thalasodendron* spp. and *Halophila spinulosa*. However, most species have their meristems below ground where exposure to low salinity is not likely to occur. Due to the ability of seagrasses living near the mouth of rivers to recover from sediment burial, we predict a low vulnerability to this exposure threat. Structurally smaller species such as *Halophila* spp., *Halodule uninervis* or some forms of *Zostera muellerii* will be more vulnerable to the impacts of sediment deposition as a small change in sediment profile will cover or erode them. This does not take into account the consequences of reduced light from river flood plumes and resuspension of sediments through wind.

In summary, seagrass can be lost or be negatively impacted when exposed to river flood plumes due to a combination of processes including: sediment deposition, water currents, toxicants, suspended sediments in the turbid plume and the long-term resuspension of sediments causing reduced light. Increased nutrients and decreased salinity are unlikely to have any negative effects. Seagrass meadows can recover from existing cyclone, storm and flood events but if more extreme events occur in the future, it may take longer for the meadows to recover. Communities may shift towards more ephemeral or dynamic types.

### 8.2.5 Light and ultraviolet radiation

A number of factors can affect light availability to seagrasses. Flood plumes carry suspended sediments and dissolved nutrients that can stimulate phytoplankton blooms. Phytoplankton blooms are generally suppressed by high turbidity during flood plumes and tend to follow after most of the sediment has settled out[53]. Wind-driven resuspension of sediments will reduce light to benthic organisms in the GBR. These events will alter light quality and quantity reaching benthic habitats such as seagrass. Cloud coverage may increase in certain regions depending upon the time of year, although an overall increase in cloud cover is expected in the northern GBR. Finally, levels of ultraviolet (UV) are predicted to increase under climate change scenarios. The expected impacts of these changes on seagrasses are depicted in Figure 8.12.

***Figure 8.12*** *Predicted causes and impact of changing light regimes on seagrasses based on climate change predictions for the GBR*



### 8.2.5.1 Exposure – light and ultraviolet radiation

Most seagrasses in the GBR will be influenced by any change to light quality and quantity[21]. Frequent small rainfall events provide chronic impacts but are constrained to regions close to the point of river discharge including coastal intertidal and subtidal habitats. Heavy rainfall events, including storms and cyclones, have the potential to transport these plumes northward across the GBR lagoon towards the mid-reef[53] where reef and deep water seagrass meadows may be affected. If these events become more intense and intermittent, as predicted under climate change scenarios, substances accumulated within the catchment during the long dry periods will be released in one large event resulting in more turbid and extensive flood plumes.

Turbid water conditions in nearshore coastal waters are sustained by the resuspension of sediments deposited during rainfall events, with near-bottom turbidity levels caused by resuspension often exceeding those within flood plumes[77,53]. Turbidity generally increases with wind speed[3] with stronger winds required to generate waves that are sufficient to reach the bottom in deeper water[53]. Coastal seagrasses in habitats of less than five metres deep are the most heavily impacted by wind-driven sediment resuspension. Intense storm and cyclone events expected to occur in climate change predictions also expose deeper meadows to resuspension events as storms can generate waves capable of moving and resuspending sediments in waters up to 20 metres[53]. Turbidity can affect light quality; blue light (400 to 500 nanometres) and red light (600 to 700 nanometres) are preferentially removed, changing its quality to a more yellow light, which is less useful for photosynthesis[86].

Furthermore, increased storm activity associated with climate change may also increase cloud cover during these events. Cloud cover has been shown to create a feedback loop where elevated temperature increases evaporation producing more clouds that reduce light and reduce temperature.

### 8.2.5.2 Sensitivity – light and ultraviolet radiation

The sensitivity of seagrasses to chronic long-term light reduction is dependent on the duration and intensity of light reduction as well as their minimum light requirements and ability to adapt to changing light. Seagrasses are capable of gross phenotypic plasticity and have numerous biochemical, physical and ecological mechanisms to cope with alterations in light. However, intense light reduction events can lead to complete loss of *Halophila ovalis* after just 30 days[88] while *Halodule* may last up to 100 days[87]. The ability of species to endure pulsed turbidity events is probably related to their ability to store carbohydrates, which can be utilised during periods of low light. The sensitivity of other species in the GBR to light reduction is not as well known. As a number of reef-colonising species are not found in more turbid coastal waters they may be more sensitive to chronic light reduction, but as they tend to form larger rhizomes capable of carbohydrate storage, it is possible they may be able to endure short term pulsed events. Subtidal coastal seagrasses that are permanently submerged are likely to be more sensitive to both pulsed and chronic light reductions than intertidal or deep water seagrasses. The sensitivity of seagrasses to light reduction can be further exacerbated by cloud cover.

Most seagrasses are sensitive to elevated levels of UV. Fluctuations in total light available can be tolerated (within a certain range), however if tolerance for UV is exceeded, a range of tissue damages will result. Thinner leaved seagrasses such as *Halophila ovalis* and *Halodule uninervis*, which are often found in intertidal areas, are known to be more susceptible to elevated UV than those with thicker leaves are[37]. There are some exceptions, for example, the thin leaved *Halophila johnsonii* from Florida (closely related to *Halophila ovalis* from the GBR[146]) is not sensitive to high levels of UV[71]. Epiphyte accumulations on the surface of leaves, although detrimental to overall light availability, can reduce the sensitivity of seagrasses to UV damage[136,12]. Recent analysis of the impact of tiny grazers of epiphytes on the leaves of seagrass supports the important role of these epiphytes in shielding seagrass leaf tissue from the full impact of UV damage (B Bendel unpublished data).

### 8.2.5.3 Impacts – light and ultraviolet radiation

Intense run-off events have led to the loss of seagrass, due primarily to reduced light penetration caused by high turbidity such as that observed in Hervey Bay in 1999[86,19]. Whether future flood plumes will result in seagrass loss depends on the intensity and duration of the plume, while the spatial scale of the impact will also depend on the spatial extent of the plume. Complete loss of seagrass will result if turbidity and light reduction persists at below the minimum light requirements for an extended duration. The tolerable level for complete light reduction is highly variable for the two studied species (*Halophila ovalis* at about 30 days and *Halodule pinifolia* at about 100 days) and is unknown for most other GBR species.

Ongoing resuspension of sediments resulting in light reduction have been linked to fluctuations in seagrass coverage[104] and to complete seagrass loss[39]. The impacts of sustained reductions in light availability due to resuspension of sediments is likely to be a reduction in seagrass depth limits and long-term impacts on meadow biomass and growth.

In nearshore coastal habitats, cloud cover accounts for about 14 to 17 percent of the variability in light availability[3] and, on average, is not likely to strongly impact seagrass survival. However, dense cloud cover is known to exacerbate the impacts of turbidity or shading. Responses to shading could be used to extrapolate to the impact of reduced light linked to cloud cover, however, the intensity and duration of light reduction associated with cloud cover is likely to be substantially less than those used in previous experiments. In regions where cloud cover is expected to increase (ie northern GBR), intense, prolonged cloud cover will exacerbate the effects of other light reducing processes, if they co-occur. Increased UV will have negative impacts on shallow intertidal seagrasses as high UV levels damage photosystems and reduce photosynthetic efficiency[37,44].

### 8.2.5.4 Adaptive capacity – light and ultraviolet radiation

Seagrasses respond to reductions in light availability through a range of morphological and physiological adjustments[148]. Some of these, such as increases in chlorophyll concentration, are responses that improve light capture and carbon fixation[79]. Other responses reduce the plant's carbon requirements, for example growth and biomass are often reduced. However, all seagrasses have threshold minimum light requirements below which such adjustments are insufficient to meet their carbon balance demands. These thresholds are not known for most seagrasses of the GBR.

Following complete loss of meadows, recovery can be rapid if conditions at the site are suitable for recolonisation. For example, *Zostera muelleri* showed complete recovery three years after a flood event in Hervey Bay[19]. Recruitment into new areas occurs primarily through seed dispersal or import of vegetative fragments, and proximity to a donor meadow may be important for recovery rates. Dynamic communities are more adapted to periods of disturbance than late successional species and therefore ongoing disturbances are likely to affect species composition.

Most species demonstrate photosynthetic damage from short-term periods of elevated UV but the long-term adaptive capacity is unknown. *Halophila johnsonii* from Florida contains UV absorbing compounds that can increase in response to elevated UV[71] and *Halodule wrightii* from Florida, is thought to have photorepair mechanisms to minimise the impact of UV on photosynthesis[136]. Whether these UV adaptation mechanisms occur in other species is unknown.

### *8.2.5.5 Vulnerability and thresholds – light and ultraviolet radiation*

Species inhabiting coastal intertidal and subtidal regions (eg *Halophila, Halodule* and *Zostera*) will be most at risk from pulsed turbidity events and are probably the least tolerant to intense light reduction (see Figure 8.7). Later successional species, such as *Thalassia*, may be more tolerant to pulsed light reduction as they have greater carbohydrate storage capacity[36]. These species tend to occupy reef habitats that will infrequently be exposed to large flood events. Therefore, recovery will be species-specific and could result in changes in the community composition.

The minimum light required to sustain meadows over longer durations is largely unknown for GBR seagrasses with the exception of *Zostera muelleri*, which has been determined to require 16 to 36 percent of sub-surface irradiance for survival[86]. Seagrasses globally have light requirements in the range of 4 to 36 percent of sub-surface irradiance[40,86]. If light availability is sustained below this level, complete loss of seagrass is expected. Within the GBR, current distributional patterns suggest that species occurring in reef habitats probably have a lower threshold for long-term light reductions as they inhabit high-light environments. We should point out however that species-specific light requirements for GBR seagrasses have not been determined and may vary beyond this range of light requirements.

## 8.2.6 Elevated carbon dioxide concentrations and ocean acidification

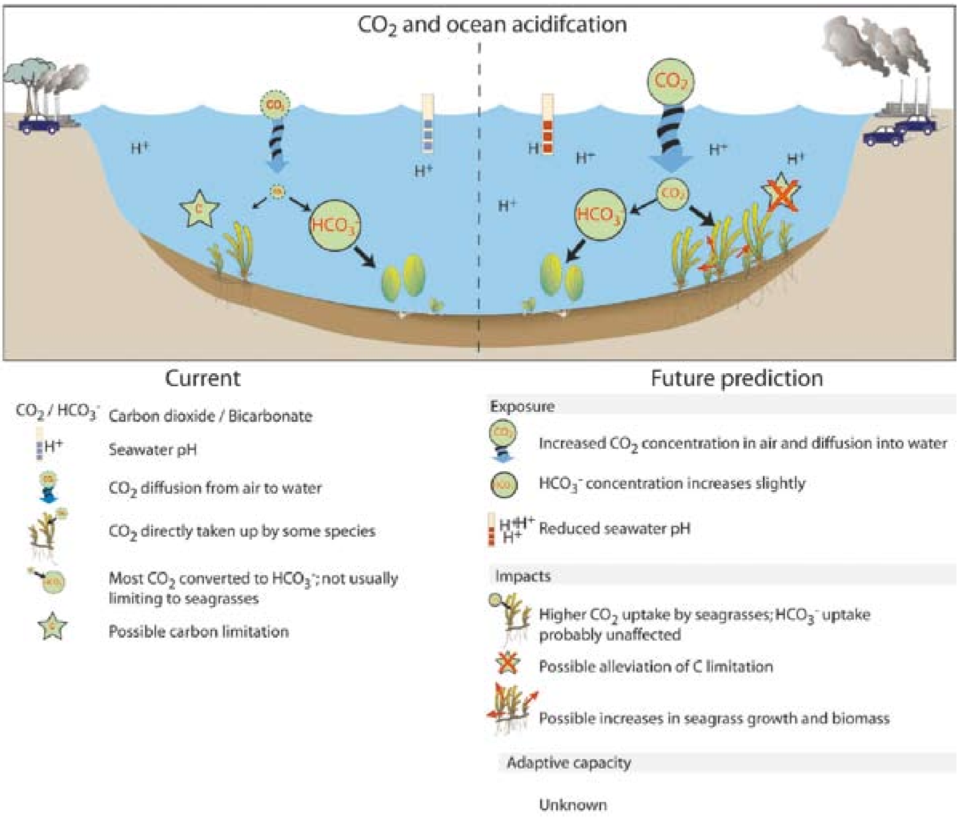
Over the 20th century, atmospheric $CO_2$ has increased by 25 percent from 290 to 350 parts per million and over the course of the coming century the concentration will have doubled. The most significant changes for seagrass physiology will be due to changes in dissolved $CO_2$ and any increase in bicarbonate ($HCO_3^-$) concentration as seagrasses can utilise both these carbon sources (Figure 8.13). The possible influence of changes to both will be considered here and collectively referred to as inorganic carbon, unless otherwise specified.

### *8.2.6.1 Exposure – changing $CO_2$ concentration*

All regions of the GBR will be influenced by the predicted elevated atmospheric $CO_2$ concentrations and ocean acidification. All seagrass habitats are within a zone of well-mixed water to 20 metres depth[53,140]. Thus all tropical seagrasses will be exposed to the increased inorganic carbon. Temperature changes will also influence the solubility of dissolved gases. Thus, water column inorganic carbon concentrations may vary across the GBR depending upon local ambient water temperature. Different seagrass species may respond to these changes in inorganic carbon and the concomitant changes in pH and bicarbonate.

Competition for inorganic carbon uptake with other marine autotrophs may also impact the ability of seagrass to access $CO_2$. Elevated photosynthetic rates of other marine autotrophs, such as epiphytes, may stimulate their growth, out-competing seagrass. Björk et al.[9] suggested that marine macroalgae

**Figure 8.13** Influences of changes in $CO_2$ concentration on seagrasses



were more efficient at concentrating inorganic carbon than seagrasses, though Beer and Koch[5] suggest that this difference will probably be negligible in reduced pH (higher $CO_2$) waters. Further research is needed to assess these interactions in a greater range of macroalgal species as well as microalgal epiphytes on seagrass leaves.

### 8.2.6.2 Sensitivity – changing $CO_2$ concentration

Most seagrasses are inorganic carbon-limited under maximum irradiance conditions. In addition, they have adapted to bicarbonate uptake or the conversion of dissolved $CO_2$ at the leaf surface[78, 79]. Two basic inorganic carbon uptake pathways exist in seagrasses (direct $CO_2$ and $HCO_3^-$), and the presence of these pathways appears to be species-specific[135,79,154]. Use of bicarbonate as an inorganic carbon source is common in tropical seagrass (eg *Halophila ovalis, Cymodocea rotundata, Syringodium isoetifolium* and *Thalassia testudinum*)[135], whereas others use enzymes to make $CO_2$ available as the inorganic carbon source (eg *Enhalus acoroides, Halodule wrightii, Cymodocea serrulata*). Seagrass species that directly use $CO_2$ will benefit from elevated atmospheric concentrations[43]. It is also expected that $HCO_3^-$ concentrations will increase slightly under elevated $CO_2$ conditions; therefore, species using bicarbonate will have some benefit from increased $CO_2$ or acidification. Zimmerman[154]

suggests that most seagrass species will be able to utilise increased inorganic carbon under the various climate change scenarios to increase their production and areal extent. However, some species of seagrass such as *Cymodocea serrulata*[128] have been shown to be carbon saturated, so irrespective of atmospheric $CO_2$ levels, those species will not have enhanced productivity as a result of elevated inorganic carbon. Unfortunately, few species have been assessed for their inorganic carbon requirements and saturation status.

### *8.2.6.3. Impacts – changing $CO_2$ concentration*

No detectable change in seagrass health or distribution has been observed as a direct result of elevated $CO_2$ concentration and at present few manipulative experiments have been performed to assess the potential impact[5,6,128]. It is generally accepted that under climate change scenarios of elevated atmospheric $CO_2$, seagrasses will not suffer[5,79,154,124], in fact, small increases in photosynthesis are expected (Figure 8.13).

### *8.2.6.4 Adaptive capacity – changing $CO_2$ concentration*

There is contrasting evidence as to whether seagrasses can adapt to an increase in $CO_2$ concentration[131] based on disparate data sets. Most seagrasses evolved during a period of higher $CO_2$ concentration than is currently available[109] (Figure 8.1). This implies seagrasses may be well suited to making adjustments to long-term increases in $CO_2$. It is expected that species in the Zosteraceae are not as well adapted to elevated $CO_2$ concentrations as members of the Hydrocharitaceae, Cymodoceaceae and Posidoniaceae, as this group evolved more recently after the Palaeocene when ambient $CO_2$ was lower. Our ability to assess species adaptability is poor due to a lack of basic data.

### *8.2.6.5 Vulnerability and thresholds – changing $CO_2$ concentration*

Seagrass responses to elevated $CO_2$ concentration or decreased pH are expected to be small and positive for most seagrass species (Figure 8.13). Not all species will benefit from higher $CO_2$ concentrations, specifically those that utilise $HCO_3^-$, and so a species shift favouring the former is possible. However, this is highly dependent on a range of other environmental variables, such as light availability, and the opposing responses to both variables may offset each other. Overall, the small pH change expected is unlikely to have a significant impact on seagrasses.

## 8.2.7 Changes in ocean circulation

Under climate change it is predicted that the major currents in the GBR will change, the East Australian Current (EAC) will move south, notably during ENSO events. There may also be a northward change in current direction and magnitude along the GBR coast and lagoon. Variations in ocean circulation may also influence heat transport processes and climatic conditions in the GBR although the extent of this influence remains obscure.

### *8.2.7.1 Exposure – ocean circulation*

Movement of the EAC south, along with the resultant change in current direction and magnitude along the GBR coast and lagoon, will alter sea surface temperature in the entire GBR, impacting coastal, deep and offshore reef seagrass communities. How sea surface temperature will change at fine scales is uncertain. Furthermore, it is uncertain how climatic conditions will vary as a result of change to heat transport in the GBR. The EAC upwells cold, saline, nutrient rich water in the southern GBR across the shelf break, and is an important source of nutrients for the region[107]. Movement of the EAC south along with the upwelling of nutrients, may impact upon offshore reef communities in the southern seagrass region. A northward change in current direction and magnitude along the GBR coast and lagoon may expose seagrass communities along the coast, in deep water and in offshore reefs to higher-energy events. Both the movement of the EAC south and change in direction and magnitude of coastal currents will be enhanced during an ENSO event.

### 8.2.7.2 Sensitivity – ocean circulation

A southward movement in the EAC and its effect on southern offshore reef seagrass communities is dependent on their reliance for nutrients from offshore upwelling. This relationship has not been quantified and so the sensitivity of seagrass communities to this event is uncertain. General sensitivity to temperature has been discussed above. An increase in magnitude of inshore northward currents in conjunction with strong south-easterly winds, tropical cyclones and severe storms will expose coastal and offshore reef (intertidal and subtidal) habitats to more energy than would otherwise exist. The direction and magnitude of inshore currents influence seed dispersal for species that distribute their seeds or vegetative fragments on the ocean surface and/or through the water column[147]. The sensitivity of seagrass communities to change in coastal and lagoon currents is dependent on species type, and their reliance upon currents for seed dispersal.

### 8.2.7.3 Impacts – ocean circulation

At present, maximum recorded current speeds in the GBR vary between one and two metres per second[152,151,107]. In association with strong south-easterly winds, tropical cyclones and severe storms, the predicted increase in magnitude of inshore northward moving currents will be further exacerbated, but it is uncertain what the current speed will be. *Zostera marina*, a northern hemisphere temperate seagrass species, can persist to varying degrees at current speeds between one and four metres per second[69,70]. The degree tropical seagrass species tolerate being exposed to high-energy currents is unknown. Negative impacts to seagrasses due to high-energy currents are a loss of seed banks, scouring, turbulent water motion and sediment movement. Changes in ocean circulation may also influence the distribution of tropical species, resulting in a more southerly distribution of species largely absent from the GBR at present (see Figure 8.4), or allow species currently limited to the subtropics (Moreton Bay) to extend farther south.

### 8.2.7.4 Adaptive capacity – ocean circulation

It is likely that adaptations in seagrasses will be changing species distributions and community compositions for many of the regions of the GBR. Little can be predicted beyond these generalisations, as the impacts themselves remain tenuous.

### 8.2.7.5 Vulnerability and thresholds – ocean circulation

The quantitative relationship between ocean circulation and seagrasses is unknown. The vulnerability of seagrass communities to change in the EAC and coastal and lagoon currents cannot be determined confidently, this remains an area of research to be explored.

## 8.3 Interactions and linkages with other ecosystem components

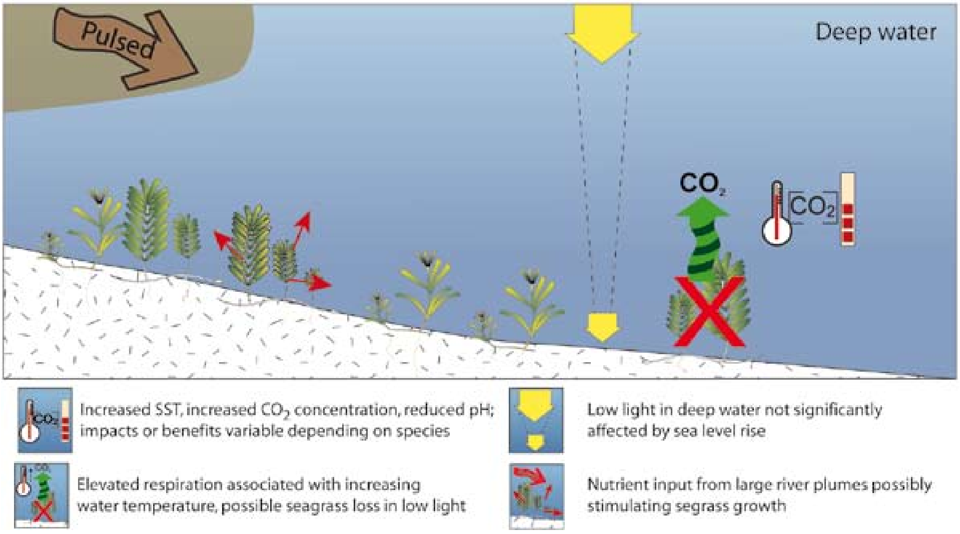
### Habitat responses to multiple stressors

The impact of multiple stressors on seagrass habitats of the GBR is somewhat speculative due to the lack of specific threshold evidence for individual stressors. However, a conceptual understanding of these stressors can be developed based on the current knowledge. Coastal seagrasses experience greater exposure to the influence of terrestrial runoff; the most direct impacts being seagrass loss due to sediment deposition reduced light availability due to turbidity, and changing salinities. In addition, higher temperatures in shallow and intertidal habitats may become inhospitable for seagrasses. Finally, sea level rise will cause a loss of seagrass at the current depth limit, particularly in turbid coastal water, and new habitat may not be suitable for seagrasses to colonise due to physical barriers or unsuitable substrate for colonisation. It is predicted that coastal seagrasses will suffer a loss of overall habitat although the scale of that loss cannot be predicted at this stage.

In contrast to coastal seagrass habitats, reef habitats do not experience the full impact of land-based inputs. The combined impact of temperature, salinity fluctuations due to heavy rainfall and an elevated sea level will potentially reduce seagrasses in these habitats. However, as the majority of seagrasses in reef habitats are nutrient limited, the influx of additional nutrients via flood plumes may increase seagrass growth.

Deep water seagrasses will be relatively protected from disturbance impacts but the combination of multiple causes for reduced light and increased respiration demands may limit seagrass survival in this habitat type (Figure 8.14). The response of seagrasses growing in deep water is difficult to assess as so little data is available regarding this important seagrass resource in the GBR.

***Figure 8.14*** *Influence of multiple stressors on deep water seagrass habitats based on predicted climate change impacts*

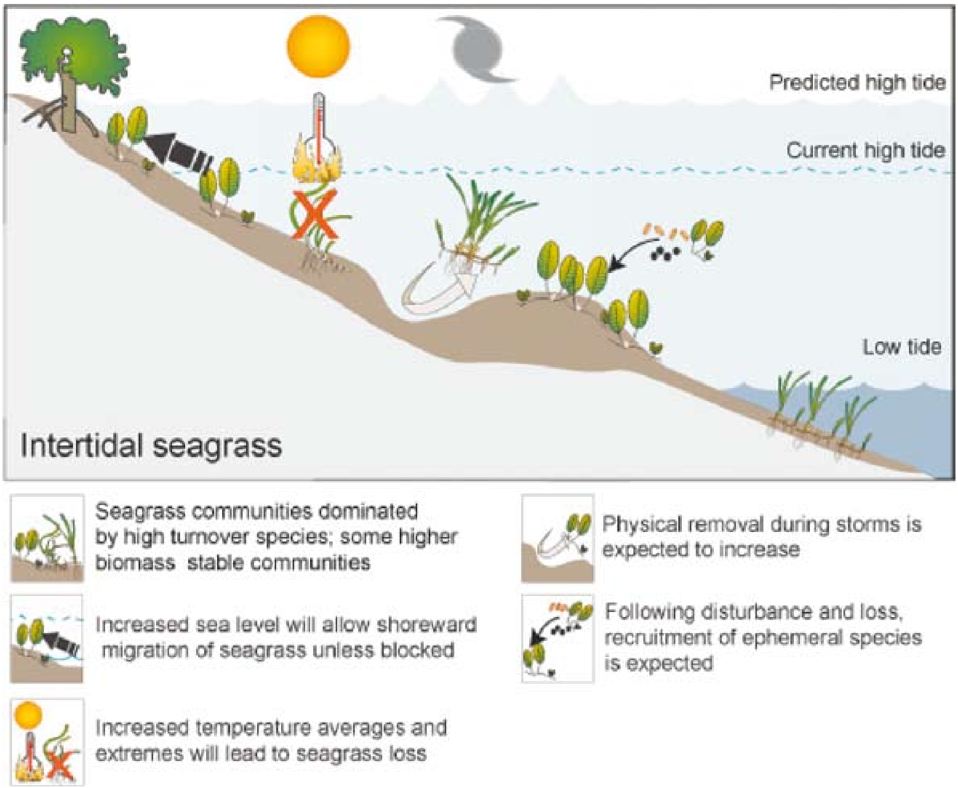


### *Seagrass habitats may experience change in community structure*

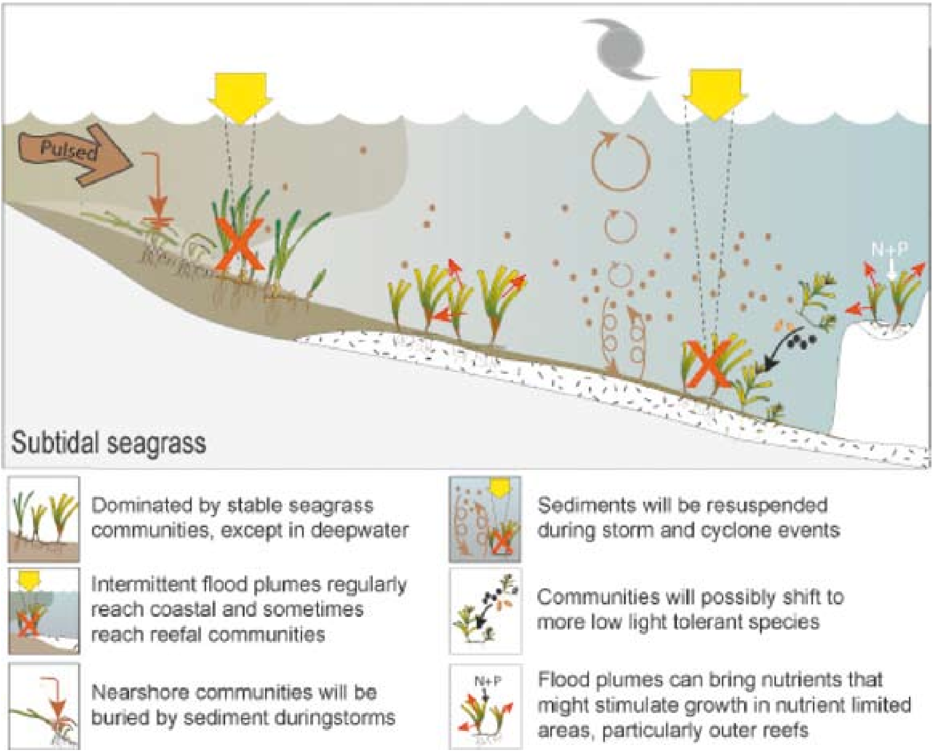
The interaction of changing environmental conditions are of particular concern in intertidal or shallow water habitats, where the combined impacts of temperature, storm and cyclone related disturbance and sea level change will result in a narrower habitat for seagrasses (Figure 8.15). Seagrass community structure in these habitats is predominantly high turnover, disturbance response species already. These seagrass communities have relatively low resilience to impacts and respond by reducing biomass, to the point of seagrass loss. They do, however, recover relatively quickly (months to years) once habitat quality improves. The intertidal and shallow-subtidal seagrass meadows that are higher biomass are more stable meadows, for example the *Zostera muelleri* meadows at Ellie Point, Cairns or Pigeon Island, Airlie Beach. Resilience of seagrasses in these higher biomass communities will be reduced locally by the impact of coastal developments such as marinas, roads and changed drainage systems which change land-based inputs or limit the ability of seagrasses to colonise potentially favourable habitat. These communities will most likely experience a shift in composition to disturbance resilient species such as *Halodule uninervis* and *Halophila ovalis*. This change in seagrass species composition will alter the associated ecological services these communities perform, although specifics of these services are poorly studied in the GBR.

***Figure 8.15*** *Influence of multiple stressors on (a) intertidal and (b) subtidal seagrass habitats based on predicted climate change impacts*

**a.**



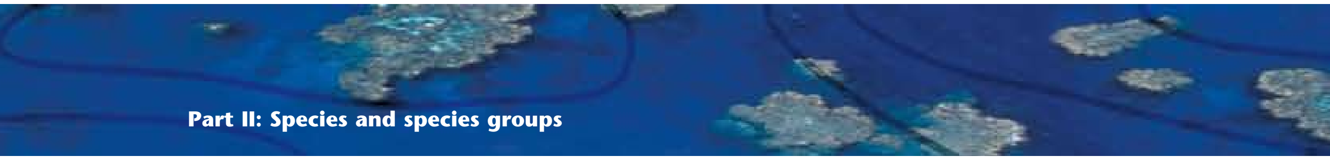
**b.**



### *Inter-community linkages*

Seagrass habitats exist in a continuum between terrestrial, freshwater, saltmarsh, mangrove, seagrass, inter-reef and coral reef habitats. In this series, seagrasses represent a buffer between the terrestrial and mangrove habitat and reef habitats. In many areas of the GBR, mangroves are the interface between the land and the sea. As a result, declines in mangrove habitats could expose seagrass communities to the enhanced effects of terrestrial inputs such as freshwater runoff, nutrients and sedimentation. In addition, in many areas, mangroves provide shelter from the influence of currents and oceanic swell providing additional habitat for seagrasses. In contrast, mangroves act as a barrier to seagrasses occupying upper intertidal and shallow-subtidal habitat and may in fact represent a limiting factor in seagrass adaptability to changing sea levels.

Where seagrass meadows occur adjacent to coral reefs, seagrasses provide food and shelter for mobile reef organisms such as fish and crustaceans[46]. In addition, seagrasses may act as nursery grounds for numerous species[23]. Seagrasses also grow within many coral reef communities throughout the GBR[21,147]. In these locations, seagrasses act to stabilise sediments, as food and shelter for many organisms and are an often-overlooked integral component of coral reef biodiversity[109]. It is possible that seagrasses will aid in buffering the impacts of climate change on coral reefs where they co-exist, although no research has been conducted on this. Given the lack of data about such interactions, the role seagrasses may play in future reef ecosystems is worthy of further exploration.



## 8.4 Major vulnerabilities to climate change

The major vulnerability of seagrass to climate change is loss of seagrass in the coastal zone, particularly near river mouths and in shallow areas (Table 8.1). The greatest impact is expected to result from elevated temperatures, initially during extreme events, eventually in a chronic manner. In addition, reduced light penetration from sediment deposition and resuspension after severe storm and rainfall events will cause seagrass loss. However, additional research on thresholds and the combined impacts of different stressors is critical to understanding the specific vulnerability of seagrasses to climate change impacts.

In addition to losses, changes in species composition are expected to occur particularly in relation to disturbance and recolonisation. Following such events, a shift to more ephemeral species and those with lower minimum light requirements is expected. If the period between events increases, it is expected that high-risk habitats will go through 'boom-bust' cycles. Such cycles pose significant risks to associated fauna such as dugong, turtle, and important fisheries species as habitat availability changes rapidly during events.

Finally, there is potential for seagrasses to increase in their extent, especially in currently low nutrient reef habitats where cumulative changes result in elevated nutrient concentrations and lower competition due to the loss of herbivores. However, it is more likely that macroalgae are better placed to take advantage of such changes, although little direct data exists to make a strong case either way.

## 8.5 Potential management responses

Mitigation of climate change is a key strategy, however as some climate change is inevitable, it is essential to protect and enhance seagrass resilience to climate change impacts. Therefore, impacts that reduce resilience need to be managed, for example, water quality and light availability. Effectively, this means limiting any factor that increases turbidity, and sediment resuspension such as flood plumes or strong winds. In short, this means avoiding many of the consequences of climate change *per se*.

Some specific high-risk factors may be mitigated directly. For example, it may be possible to reduce sediment, nutrient and toxicant inputs by improving quality of water entering the GBR or by trapping inputs in coastal buffer zones. Ongoing efforts to treat wastewater are essential to this process. Limiting soil erosion in catchments will not only improve catchment health but will have the downstream benefit of reducing sediment loads, turbidity, toxicants and nutrient inputs into the coastal ecosystem and subsequently seagrasses. In addition, it will be essential to minimise practices that physically disturb seagrasses or have downstream impacts of physical disturbance. Thus coastal development and the construction of marinas, channel dredging or boat harbours should consider the impact on seagrass habitat. Potential point source discharges of nutrients, freshwater or toxicants may also be the source of disturbances.

Management needs at the ecosystem diversity level are more complex. For example, dugong grazing has a strong influence on seagrass community structure and a decline in grazing will have an impact on seagrass habitats. Generally seagrasses are protected due to their role as a food source for dugong or as fisheries habitat, and as such these interactions are well recognised. However herbivores also play a role in maintaining seagrasses as some (eg fish and invertebrates) graze epiphytes off the leaves

of seagrass. The loss of such grazers may enhance seagrass susceptibility to light reduction.

***Table 8.1*** *Summary of major impacts on seagrass based on predicted climate change scenarios for the GBR where:* predicted direction of change *represents loss, gain or fluctuation compared to current state, including if a change in community might be expected;* Vulnerability *represents most likely habitats to be affected;* Adaptability *represents how resilient a seagrass community is to impacts;* Significance *represents an indication of the scale and likelihood of impact to seagrass meadows within the GBR*

| Impact | Direction of change | Vulnerability | Adaptability | Significance |
|---|---|---|---|---|
| Temperature | Loss and community shifts | Shallow intertidal and shallow subtidal | Ephemeral species – high<br>Persistent species – moderate to poor | Large areas across the range<br>Highly likely |
| Sea level rise | Loss | All coastal habitats | Ephemeral species – high<br>Others – unknown | Large areas across the range<br>Moderately likely |
| Disturbance (cyclones and major storms) | Loss and intermittent gains and community shifts | All shallow habitats (less than 5 metres) | High where potential recruitment | Localised<br>Highly likely |
| Flood plumes and rainfall | Loss and community shifts | All coastal habitats | High where flood plume does not persist | Localised<br>Highly likely |
| Light and UV | Small potential loss but largely unknown | All habitats (light)<br>Shallow and intertidal (UV) | High where change is ephemeral, low otherwise | Regionally and locally<br>Limited likelihood |
| $CO_2$ and pH | Unknown impact, some small theoretical potential for loss and gain | All shallow habitats | High within ranges predicted | Regionally and locally<br>Limited likelihood. |
| Ocean circulation | Loss and gain theoretical including community shifts | All habitats | Unknown | Regionally |

* Highly resilient communities should recover quickly (months to years), moderately resilient should recover (although timescale may vary), and poorly resilient communities may not recover

The eventual survival of seagrass will be linked to factors related to the rate and magnitude of climate change and other environmental stressors that occur in coastal habitats. For example, coastal development probably reflects the major threat to seagrass habitats at present through its ongoing impact on water quality. Thus focusing management responses on reducing these impacts will assist in making seagrass meadows resilient enough to survive the impacts of climate change.

## 8.6 Further research

Species-specific tolerances across broad geographic and environmental gradients should be established including, the minimum and maximum light requirements to enable prediction of thresholds and more specific management strategies. In addition, factors to assess include:

- optimal temperature range,
- salinity range,
- pH range,
- maximum current velocity,
- sheer stress,
- toxicant exposure,
- nutrient exposure,
- and the interaction of these factors.

To develop predictive models of climate change impacts it will be important to establish species-specific thresholds for growth (vegetative growth rates and production), survival and resilience for the whole life history of seagrasses. At present, research has concentrated on responses to light limitation and nutrient enhancement in the GBR, yet many crucial information gaps remain. Even fewer data exist on the influence of toxicants, salinity, temperature and pH. The influence of these parameters should not only include standing biomass but flowering, seed production, seed germination, seedling growth and seedling survival as these are the factors that limit recovery potential.

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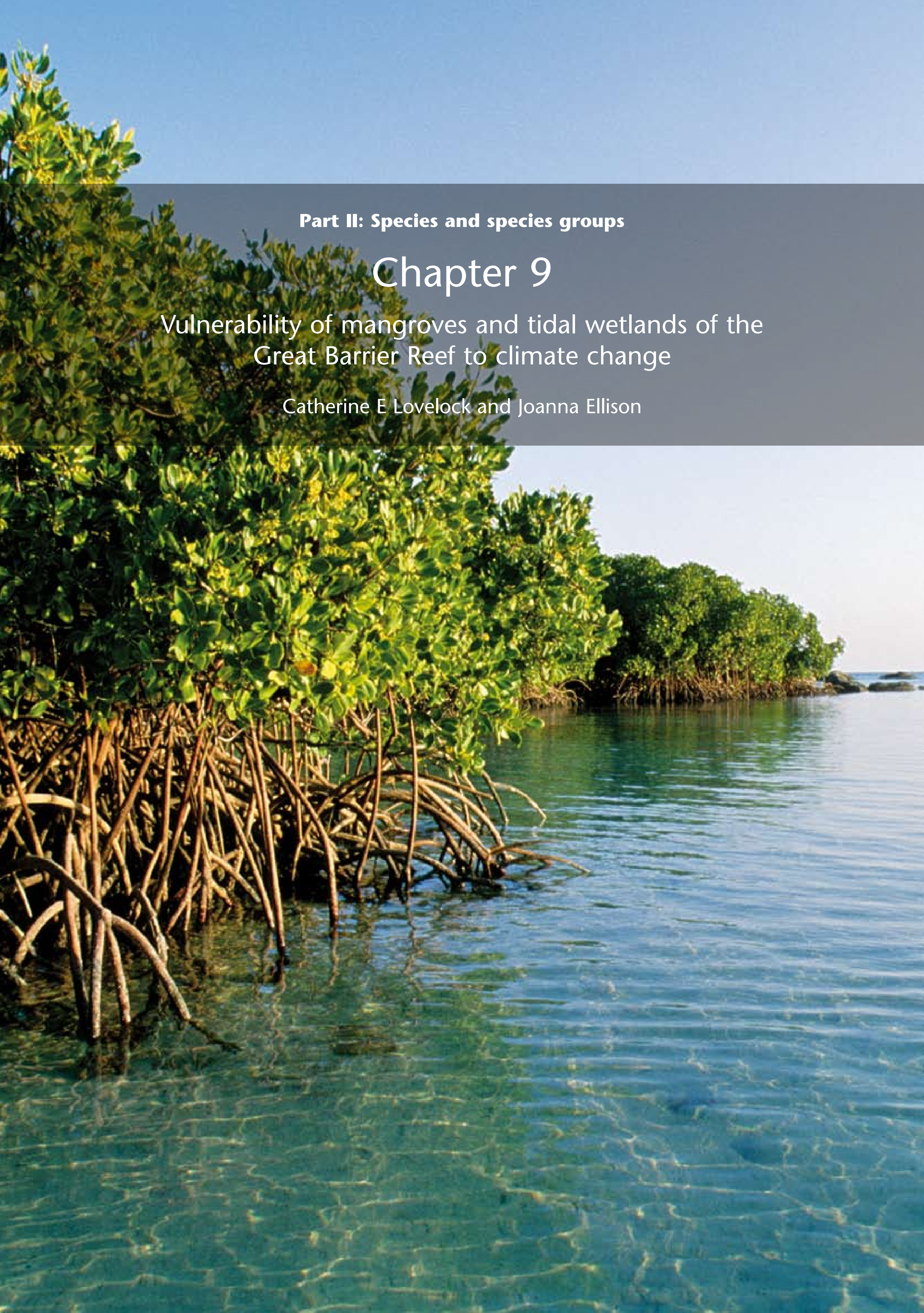
Part II: Species and species groups

# Chapter 9

# Vulnerability of mangroves and tidal wetlands of the Great Barrier Reef to climate change

Catherine E Lovelock and Joanna Ellison



## 9.1 Introduction

Climate change will have an enormous influence on the intertidal wetlands of the Great Barrier Reef (GBR). Increases in atmospheric carbon dioxide ($CO_2$) concentrations and associated increases in air and sea temperatures, rising sea level, changes in oceanic circulation, rainfall patterns and frequency and intensity of storms are highly likely to affect the physiology, ecology and ultimately the stability of wetland habitats (Table 9.1). The intertidal position of mangroves, salt marshes and salt flats makes them particularly vulnerable to changes in sea level, although other climate change factors will also exert a strong influence on wetland communities (Table 9.1). Past rises in sea level have led to increases in the area of mangroves in northern Australia[186]. However, past climate change has occurred with limited human modification of the coast compared to current levels of development. Human activities have resulted in loss of wetlands, disruption to connectivity, enhanced availability of nutrients, changed sediment dynamics and the creation of structures that will prevent landward migration of wetlands with sea level rise (eg roads, berms, bunds and sea walls). Many of these human impacts will reduce the resilience of intertidal wetlands to climate change. To conserve the intertidal wetlands of the GBR and the ecosystem services they provide, we will need to manage the coastal zone in a way that enhances the resilience of mangroves, salt marshes and salt flats during climate change.

***Table 9.1*** *Predicted effects of climate change factors on mangroves and key references*

| Climate change | Processes affected | Likely impact | References |
|---|---|---|---|
| Altered ocean circulation patterns | - Dispersal<br>- Gene flow | - Changes in community structure | Duke et al.[73], Benzie[25] |
| Increased air and sea temperature | - Respiration<br>- Photosynthesis<br>- Productivity | - Reduced productivity at low latitudes and increased winter productivity at high latitudes | Clough and Sim[55], Cheeseman et al.[49], Cheeseman[48], Cheeseman et al.[50] |
| Enhanced $CO_2$ | - Photosynthesis<br>- Respiration<br>- Biomass allocation<br>- Productivity | - Increased productivity, but dependent on other limiting factors (salinity, humidity, nutrients) | Ball et al.[20] |
| UVB radiation | - Morphology<br>- Photosynthesis<br>- Productivity | - Few major effects | Lovelock et al.[113], Day and Neale[66] |
| Rising sea level | - Forest cover<br>- Productivity<br>- Recruitment | - Forest loss seaward<br>- Migration landward, but dependent on sediment inputs and other factors (Table 9.3) and human modifications to the landscape<br>- loss of salt marsh and salt flats | Ellison and Stoddart[84], Woodroffe[188], Morris et al.[126], Semeniuk[158], Cahoon et al.[42], Rogers et al.[152] |

| Climate change | Processes affected | Likely impact | References |
|---|---|---|---|
| Extreme storms | - Forest growth<br>- Recruitment reduced<br>- Reduced sediment retention<br>- Subsidence | - Reduced forest cover | Woodroffe and Grime[189], Baldwin et al.[16], Cahoon et al.[42] |
| Increased waves and wind | - Sedimentation<br>- Recruitment | - Changes in forest coverage, depending on whether coasts are accreting or eroding (interaction with sediment stabilisation from seagrass loss) | Semeniuk[158] |
| Reduced rainfall | - Reduction in sediment supply<br>- Reduced ground water<br>- Salinisation | - Loss of surface elevation relative to sea level<br>- Mangrove retreat to landward<br>- Mangrove invasion of salt marsh and freshwater wetlands<br>- Reduced photosynthesis<br>- Reduced productivity<br>- Species turnover<br>- Reduced diversity<br>- Forest losses | Rogers et al.[151, 152], Whelan et al.[182], Smith and Duke[168] |
| Reduced humidity | - Photosynthesis<br>- Productivity | - Reduced productivity<br>- Species turnover<br>- Loss of diversity | Ball et al.[20], Clough and Sim[55], Cheeseman et al.[49], Cheeseman[48] |
| Enhanced rainfall | - Increased sedimentation<br>- Enhanced groundwater<br>- Less saline habitats<br>- Productivity | - Maintain elevation relative to sea level<br>- Maintenance of surface elevation<br>- Increased diversity<br>- Increased productivity<br>- Increased recruitment | Rogers et al.[152], Whelan et al.[182], Krauss et al.[109], Smith and Duke[168] |

Conservation of mangrove and salt marsh habitats is critical for sustained coastal productivity because of the high value of the ecosystem services they provide[56,85,98] (Tables 9.2 and 9.3). Mangroves occupy approximately 1,000,000 hectares of the intertidal zone of rivers, embayments and islands of Australia, with the majority of areas occurring in Queensland, Northern Territory and Western Australia[97,170]. The GBR has approximately 20 percent of Australia's mangrove resources (207,000 hectares). Salt marshes and salt flats occupy an approximately equivalent area as mangrove forests within the GBR[a]. Changes in the extent and function of mangrove forests, salt marshes and salt flats

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[a] www.ozestuaries.org

with global climate change could potentially have large affects on the coasts and nearshore waters of the GBR lagoon. For example, a loss of mangrove forests could reduce banana prawn landings or result in the liberation of a proportion of the huge pool of carbon stored in stabilised wetland sediments to coastal waters and the atmosphere (Table 9.3).

**Table 9.2** *Outline of some of the major ecosystem services provided by mangroves, salt marshes and other wetlands within the GBR and the processes potentially impacted by climate change*

| Ecological Services | Impact |
|---|---|
| Habitat | Fisheries and diversity |
| Nursery for fauna | Fisheries and diversity |
| Sediment trapping | Water quality |
| Carbon storage in sediments and biomass | Atmospheric carbon cycling |
| Nutrient cycling | Water quality and coastal waters productivity |
| Hydrological damping | Water quality, protection from storms, erosion and tsunamis |

The ecosystem services provided by mangroves, salt marshes and salt flats include biofiltration, carbon and nutrient retention and cycling, physical protection of coasts during storms and other large scale disturbances, and habitat for fauna, algae and microbial communities, many of which are confined to wetland habitats (Tables 9.2 and 9.3). Loss and degradation of mangroves and other tidal wetlands have occurred because of clearing, modification for human uses and through pollution of coastal waters[2,181,3,5,142]. This has resulted in an estimated global reduction in mangrove cover of 35 percent since the early 1980s, with a reported 14 percent loss in cover in Australia from 1983 to 1990[181,5]. Although there is legislative protection of intertidal wetlands in Queensland, human modifications within the coastal zone will reduce the resilience of ecosystems, making them more vulnerable to environmental pressures like climate change[82,45].

In this chapter, we first give a brief account of intertidal wetlands within the GBR and then provide a qualitative assessment of the exposure, sensitivity and vulnerability of mangroves, salt marshes and salt flats to climate change. We provide a generalised account of ecosystem services (Table 9.3), and give an outline of models and methods that are currently used in assessing vulnerability of wetlands to climate change. We conclude this chapter with a list of issues for environmental managers and significant gaps in our knowledge that need to be filled in order to better understand changes in the extent, community composition and functioning of mangrove habitats that are occurring with climate change; and place the impacts of these changes within the context of continued sustainability of the GBR.

*Table 9.3* *Summary of magnitude of some of the ecosystem services provided by mangroves*[b]

| Ecosystem service | Stocks | Rate of ecosystem service or productivity | References and assumptions |
|---|---|---|---|
| **Fisheries** | | | |
| Seaward fringe | Fish 20 to 290 kg per ha | Prawns 450 to 1000 kg per ha per year | Robertson and Blaber[146], Blaber[27] |
| High intertidal | Fish 6 kg per ha | | Mazumder et al.[124], salt marsh, reported as 0.56 fish $m^{-2}$ (assuming 1 fish = 1 gram) |
| **Sediment trapping** | | | |
| Seaward fringe | | 50 to 600 Mg per ha per year | Furukawa et al.[96], Saenger[155], Alongi et al.[13] |
| High intertidal | | 4 Mg per ha per year | Furukawa et al.[96] – 5 g $m^{-2}$ $tide^{-1}$, assume tidal inundation 20 percent of each year |
| **Nutrient and carbon retention and cycling** | | | |
| Carbon storage | 385 Mg C per ha | 3000 to 3500 kg per ha per year | Chmura et al.[52] (reported as 0.0055 grams C per $cm^{-3}$ – assume soils are 1 metre deep and average bulk density of 0.7 grams per $cm^{-3}$<br>DM Alongi, unpublished data. |
| Nitrogen storage | 20 Mg N per ha | 140 to 170 kg per ha per year | Lovelock unpublished data derived from ratio of C:N of 20 in sediment organic matter |
| Carbon export | | TOC: 2640 kg C per ha per year DOC: 500-1500 kg per ha per year | DM Alongi, unpublished data. Dittmar et al.[67], Twilley[179], Ayukai et al.[15] |
| Nitrogen export | | Total 35 kg per ha per year<br>DON 25 kg per ha per year<br>PON 18 kg per ha per year | Alongi et al.[7] |

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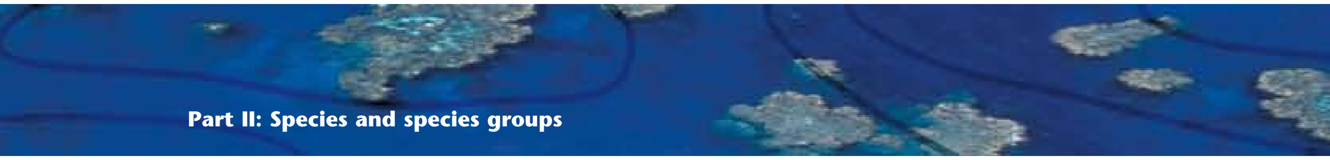
b The value of fisheries habitat and sediment trapping is considered for seaward fringing mangroves (low intertidal) and high intertidal. Key: C = carbon; N = nitrogen; TOC = total organic carbon; DOC = dissolved organic carbon; DON = dissolved organic nitrogen; PON = particulate organic nitrogen, ha = hectare , Mg = mega gram or 1 000 000 g



### 9.1.1 Mangroves, salt marshes and salt flats

Mangroves, salt marshes and salt flats have communities of plants with special physiological and morphological adaptations that allow them to grow in the intertidal zone of the marine environment[46,114]. Mangroves are mainly comprised of woody tree species, salt marshes are comprised of short herbaceous and woody species and salt flats are encrusted by films of cyanobacteria and other desiccation tolerant microorganisms. The positions of these communities in the intertidal zone make them particularly sensitive to sea level rise and other factors that influence hydrology of the intertidal zone. Accurate elevation surveys at a range of sites (Bermuda, West Papua, Hinchinbrook Island and the Darwin Harbour) have shown that the position of mangroves relative to mean sea level is variable, but often occurs below mean sea level[29,184,79,81]. Mangroves can occur up to 0.4 metres below mean sea level at the seaward edge of the mangrove and above the mean high tide at the landward edge of the mangrove[79,81]. Salt marsh communities occupy a position landward of mangroves or higher in the intertidal zone, often intergrading with terrestrial vegetation on the landward edge[1]. Salt flats also occur landward or higher in the intertidal than mangroves and are best developed in areas with high evaporation and low rainfall. These environmental conditions are unfavourable for the development of extensive salt marsh and mangroves[93] but instead favour the development of cyanobacteria dominated crusts or mats. The position of mangroves, salt marshes and salt flats relative to each other and to sea level gives rise to the high vulnerability of these habitats to sea level rise and highlights the potential for disruption and relocation of vegetation zones and the structure of the vegetation with climate change.

The patterns in diversity of plant species within salt marshes and mangroves and of microorganisms on salt flats are correlated with factors that will be influenced by climate change[72,1,153]. For example, within the GBR, mangroves increase in diversity from south to north[177,72] while salt marsh species diversity increases from north to south[62]. Mangrove tree species diversity is also influenced by rainfall, with higher diversity of mangrove tree species in moist compared to arid estuaries[168]. Additionally, intertidal microbial mat community diversity declines with longer periods of desiccation higher in the intertidal[153].

Mangrove forest structure is characterised by zones of tree species, in patterns that often run perpendicular to the shore, and by strong gradients in tree height[115]. Tree height declines from tall forests fringing open water or rivers (up to 50 metres) to shorter forests (less than 1 metre) and salt marsh and salt flats on the landward margins. The variation in forest structure, habitat type and productivity across the intertidal region is related to the underlying geomorphology[187,184,158] that reflects the strong spatial patterns in inundation frequency, sediment and nutrient inputs, salinity and biological processes (eg bioturbation and predation)[167,156,18]. Many of these processes are influenced by climate change (Table 9.1) and are also affected by human activities.

Consideration of how vegetation structure will be altered by climate change is important because vegetation structure influences ecosystem function[187,184,158,180]. Variation in tree height of mangrove forests is correlated with primary productivity[156]. Additionally, different species of mangroves have different morphological and biochemical properties that influence ecosystem processes. For example, tissue of *Avicennia* spp. is richer in nitrogen than that of *Rhizophora* spp., resulting in differences in rates of primary consumption and decomposition[178,144,145,166,174,59,28]. Faunal communities are also influenced by forest structure[4,6] and have flow-on effects on ecosystem function. For example, crabs that bury and shred leaf litter and make burrows influence carbon and nutrient cycling and the hydrological properties of mangroves[143,140].

Although most mangrove forests within the GBR are within estuaries and embayments, there are many mangrove-dominated islands offshore. Steers[172] first described these low wooded islands as reef top associations of windward shingle ridges that provide protection for leeward sand cays and intermediate mangrove swamps on patch reefs. In the northern GBR, 34 low wooded islands have been found to occur over 4 degrees of latitude extending north from Low Isles (16° 23′ S, 145° 34′ E)[176]. More recently, Neil[130] classified Green Island in Moreton Bay (27° 25′ S) as a low wooded island, with differences from the northern islands only due to the lower temperatures and higher wave energy conditions of southern latitudes. While mangroves of low wooded islands are smaller in extent than mainland mangroves, mangroves of low wooded islands have close connections with the reefs and seagrass beds, providing fish breeding habitat and mangrove based food webs within reef-dominated settings. They also provide essential nesting sites for migratory birds (eg Imperial Pied Pigeon). Mean elevation of mangrove/lagoon margins on the low wooded islands was found to be 0.36 metres below mean sea level (Ellison, unpublished data). Their low position in the intertidal zone and limited sediment supply to the islands may make them highly vulnerable to sea level rise.

In arid areas of the GBR, landward mangrove forests are often replaced with extensive high intertidal cyanobacterial encrusted salt flats and salt marshes that are dominated by succulent salt marsh species[168]. Sedge-like salt marshes also occur on the landward edge of mangroves, and are well developed where fresh water inputs are high[1,35]. Australian tropical salt marsh communities are characterised by low stature but highly productive species that support a wide range of fauna[1]. Salt marsh and salt flat habitats are among the most vulnerable to climate change. They are often highly disturbed by human activities[3]. Urban, industrial and agricultural developments within or on the landward edge of salt marshes will prevent their migration upslope in response to rising sea level. Additionally they are being squeezed by mangrove encroachment on the seaward edge[3,152]. Grazing, weeds and vehicle traffic add to the pressures on salt marshes further reducing the resilience of salt marshes to global climate change[3].

## 9.1.2 The role of mangroves in the Great Barrier Reef

### *9.1.2.1 Physical structure*

Mangrove tree species have aerial roots of varying architectures (eg stilts, pnuematophores, knees and buttresses) that have a significant impact on the function of mangrove-dominated estuaries. Lower stems and root structures, including pneumatophores cause friction within wetlands, slowing water velocities and resulting in deposition of sediments[96,185]. Through the process of trapping sediments and particulate organic matter[96,9,13] water quality in adjacent habitats (seagrass and coral reefs) is enhanced[185].

The role of mangrove roots in preventing coastal erosion is critical[95,121,122,119,123]. They also may have some role in protection from storm surges and tsunamis[60,63,58]. Roots also bind sediments preventing resuspension[190,109]. They provide sites for associated flora (eg macroalgae), that adhere to above ground roots[149], further increasing the friction to tidal flow. The fauna associated with aboveground roots graze on algal and microbial material and benefit from protection from predation[139,111,147,6,163].

### *9.1.2.2 Carbon and nutrient storage and cycling*

One of the key ecosystem services of mangroves, salt marshes and salt flats is the retention of carbon and nutrients within aboveground biomass and sediments. In mangroves, approximately half the nutrient and carbon stocks can be in the sediments[11]. Mangroves have higher soil carbon contents than salt marsh soils, and both exceed carbon contents of most terrestrial soils making them particularly important in regional and global carbon and nutrient budgets[179,52,10,12].

Growth of mangroves within the GBR is limited by nutrient availability[31]. (Lovelock and Feller, unpublished data). Nitrogen fixation in mangroves can occur at high rates (eg Woitchik et al.[183]) but imported nitrogen is required to meet the demand of primary production of the forests[30,10]. Very little nitrogen is lost from undisturbed mangroves via denitrification or in tidal exchange[7] due in part to the high efficiency of internal cycling within tree tissues[90,91] and sediments[13]. Development within the catchments of the GBR and nutrient enrichment of coastal waters can alter nutrient cycling in mangroves, resulting in leakage through enhanced denitrification[13] and reductions in the efficiency of tree internal nutrient cycling[91,92]. How carbon and nutrient cycling processes are influenced by factors associated with global climate change is not known, but increases in temperature and changes in rainfall may have significant effects on microbial processes and nutrient retention in forest biomass.

Although there is evidence for net uptake of carbon and nutrients by mangrove ecosystems, there is exchange among mangroves and adjacent regions with mangroves providing important carbon and nutrient subsidies to coastal waters[8,33,67]. Export of detrital particulate matter and dissolved nitrogen and carbon from mangroves and intertidal wetlands can be substantial[179,8,67] (Table 9.3), but seasonally variable[32,15], indicating that changes in rainfall patterns could affect outwelling of materials from mangroves. Salt flats in the high intertidal zone fix and sequester carbon and nitrogen within cyanobacterial crust communities[134,30,107]. Phosphorus is also sequestered in salt flats due to evaporation of seawater, rain and fresh water inputs[141]. These materials accumulated on salt flats can also be released in seasonal pulses with fresh water flow or during high tides[141].

### *9.1.2.3 Fauna and dependencies*

Mangrove forests and associated salt flats and salt marsh support a diverse and abundant fauna. While invertebrates and fish are highly diverse groups that are abundant in mangrove habitats, many species of reptiles (including turtles, crocodiles and lizards), birds and mammals also use mangroves as habitat[145,6,154,108]. Many species of mobile fauna access mangrove and associated habitats seasonally when the tide permits, while others are resident. The mangrove – salt marsh/salt flat habitat can be viewed as a complex connected mosaic of habitats that are intermittently accessible to mobile fauna with affinities to reefs and other subtidal habitats[118,159]. These mobile fauna also have a role in the transfer of materials between habitats through grazing, predation, and excretion[137,160]. The contribution of animals to material exchange between mangroves and other adjacent habitats could be similar to or exceed the exchange of particulate and dissolved material with tidal flow[137].

Some of the most conspicuous fauna in mangrove forests, due to their burrows, are crabs and mud lobsters. Crabs perform critical ecological functions, influencing forest structure by consuming propagule[s167], aiding in processing of leaf litter, oxygenating the sediments, and contributing to surface friction and thus to slowing water movement that facilitates fluxes of nutrient and other materials between mangrove sediments and tidal waters[141]. Crabs are consumed by large predatory fish[160] but also produce copious larvae, which are an important food source for many juvenile fish

utilising mangroves[143]. Mangroves also support a wide diversity of other invertebrates, for example[153] species of macrobenthic species were recorded from Missionary Bay[6].

Crab species, and other fauna partition the intertidal zone, with species having a preferences for differing inundation regimes. High intertidal salt marshes, which in some areas may be most vulnerable to sea level rise, have at least 13 species of crabs[6,124]. Although there are many studies of fish use of fringing mangroves[87], there is little knowledge of transient use of high intertidal salt marsh and salt flat areas. In a recent study of fish abundance in high intertidal salt marsh habitat, the abundance of fish was greater in the salt marsh than in the mangroves when adjusted for water volume, suggesting the high intertidal may provide important resources for fish[124]. Moreover, some invertebrate species appeared to be confined to feeding in the salt marsh – mangrove ecotone[100] adding further impetus for conservation of these areas with climate change.

Arboreal residents in mangroves are also highly diverse and abundant. These include spiders, ants, beetles and other insects, bats and birds. Some are specialists on mangrove flora (eg leaf miners, wood borers, seed and insect feeders) and many have important effects on forest growth, structure and recruitment[133,145,89,88].

#### *9.1.2.4 Fisheries*

Mangroves are nurseries for fish and crustaceans. This is one of the key attributes of mangroves that contribute to their high economic value[146,23,22]. Along the Queensland coast, as in other locations, mangrove cover is positively correlated with fisheries landings[27,118]. In the study of Manson et al.[118] the relationship between mangrove area and perimeter (edge) was significant for banana prawns, mud crabs and barramundi, which are known to spend part of their life cycles in mangroves, but were also significant for other species not directly associated with mangrove habitats (eg tiger prawns, blue swimmer crabs and blue threadfin). These results indicate that mangroves provide resource subsidies to connected habitats that lead to increased fish stocks. Investigation of fish diets using stable isotope techniques also indicated that mangrove resources make a significant contribution to fish diets in species that are not resident in mangroves[125]. The single offshore commercially important species included in Manson et al's[119] analysis, coral trout, did not show a significant association with the area of mangrove habitat. However, in other regions in the world mangroves are known to support ecologically and economically important fish species[127,108,21,128,129,51].

Connectivity of mangroves with other adjacent habitats has been observed to increase productivity. For example, close proximity of mangroves and seagrass enhanced productivity of many species[129,164,159]. Although there are few studies of faunal dependence on high intertidal habitats, it is likely that for some species access and connectivity to the high intertidal area is important for enhanced total productivity[124] (see chapter 19).

### 9.1.3 Critical factors for mangrove survival

#### *9.1.3.1 Physiological limits to tree growth*

Although mangrove trees are adapted to being inundated with salt water, there are physiological limits to their capacity to withstand inundation. Mangroves are sensitive to increases in the frequency and duration of flooding that will occur with sea level rise[116,83]. As the frequency and duration of inundation increases, growth of trees will decline and forests may retreat landward. The underlying coastal topography or bathymetry (the extent and slope of coastal plains) influences the frequency and duration of inundation and thus modifies exposure to sea level rise, with truncated, steeply sloping coastlines having the greatest exposure. Tidal range and sediment dynamics, in conjunction with other climatic and biological variables, will also influence the impact of sea level rise on mangrove growth and survival (see section 9.2.5).

Both mangroves and salt marsh plants have their roots in the marine environment, but for most of the time have their leaves in the air, taking up gaseous $CO_2$ via their stomata during photosynthetic carbon gain. Stomata are sensitive to $CO_2$ concentrations, temperature, humidity and salinity of soils, and thus mangrove and salt marsh productivity is likely to be affected by enhanced $CO_2$, ultraviolet B (UVB) radiation, air and sea temperature and altered patterns of rainfall[19 20,55] (Table 9.1). Additionally, mangrove species have differing tolerances to environmental conditions[54,17,112]. Thus some species are likely to be more sensitive to climate change than others, ultimately resulting in changes in species composition of the tree community and concomitant alterations in ecosystem function and associated faunal communities. The paleontological data indicate that the Rhizophoraceae had greater dominance during periods of past sea level rise than they have presently[47,57,99,102]. This may suggest that the area of mangrove dominated by Rhizophoraceae could expand in the future, possibly at the expense of other species.

Species of mangroves from the family Rhizophoraceae are also particularly sensitive to physical damage inflicted by wind or hail. These species cannot be coppiced, having no epicormic buds from which to resprout after canopy damage[177,16]. Species from the Rhizophoraceae dominate forests of northern Australia and elsewhere in the tropics. Thus, *Rhizophora* forests may be particularly adversely affected by enhanced cyclonic frequency or intensity and other disturbances that damage aerial parts of trees.

#### *9.1.3.3 Limits to faunal distributions*

Many fauna associated with mangroves are mobile, either having larvae that are distributed within the water column, or populations that can migrate to more suitable habitat with changes in forest structure and productivity. Fauna that are confined to habitats that are at risk from sea level rise (eg high intertidal salt marsh) will be more susceptible to climate change than those using habitats that can migrate spatially, but may not be greatly reduced in area (eg seaward mangrove fringes). Mangrove losses that may occur with increased frequency and intensity of storms are likely to reduce diversity and abundance of fauna, as has been seen with other disturbances[118]. Changes in the availability or spatial arrangement of interconnected habitats (seagrass – mangroves – high intertidal), due to sea level rise, storms damage or human activity could also have a negative impact on fauna and food webs (chapter 19).

## 9.2 Vulnerability of mangroves to climate change

### 9.2.1 Changes in ocean circulation

Since mangroves have water-dispersed propagules, dispersal may be influenced by changes in oceanic circulation patterns. There are few data assessing the connectivity of populations of mangroves for the region, but a study of genetic variation in the common mangrove species *Avicennia marina* indicated

separate populations that do not currently interbreed[73,25]. Although most mangrove propagules and other debris are contained within estuaries, because of hydrological properties of estuaries[185], changes in oceanic circulation (Steinberg chapter 3) may influence dispersal and thus the genetic structure of mangrove populations. Enhanced gene flow among separated populations may increase the adaptive capacity of mangrove species. Introductions of northern mangrove species to more southern localities may also be possible (eg studies on drift seeds by Hacker[101], Smith et al.[165]) and could increase the diversity and productivity of southern mangrove communities, but range-shifts and introductions of northern mangrove species to southern locations have not yet been documented.

### 9.2.2 Changes in temperature

Plant and soil biochemical processes will be affected by increases in water and air temperatures. Two key processes that determine productivity; photosynthetic carbon gain and respiration, are highly sensitive to temperature. Photosynthesis in mangroves in much of the tropics is limited by high midday leaf temperatures which drive high vapour pressure deficits between leaves and air, resulting in stomatal closure[55,48,50]. In contrast, photosynthesis is limited by low temperature at southern latitudes[173]. Increases in temperature combined with declines in humidity and rainfall could reduce productivity in some northern sites by accentuating midday depressions in photosynthesis. Conversely increasing primary production would be expected at southern latitudes through increases in the length of the growing season. The effects of temperature on primary production are likely to be strongly influenced by other climate change and environmental factors that influence stomatal aperture and photosynthetic rates (eg rainfall, humidity and nutrient availability).

Respiration ($CO_2$ efflux) from plants and microbial communities in sediments approximately doubles with every 10°C increase in temperature. The predicted 2°C increase in temperature (Lough chapter 2) could therefore increase plant and soil respiration by approximately 20 percent, resulting in reduced net carbon gain, increased methane emissions and decreases in soil carbon storage[64]. As mangroves and salt marshes have large carbon and nutrient stores in soils and plant biomass[148,179,52] (Table 9.3) increases in temperature and associated increases in respiration may have negative effects on carbon balance. These effects on carbon balance may not be matched by increases in production, which in some cases, particularly in northern regions, may be reduced (eg Clark[53] for terrestrial forest ecosystems). There are significant gaps in our knowledge of how increases in temperature will influence the balance between plant productivity, respiration and microbial activity in mangroves and associated wetlands of the GBR.

### 9.2.3 Changes in atmospheric chemistry

Carbon dioxide is the substrate for photosynthesis and influences respiration. Due to the sensitivity of these key physiological processes to elevated $CO_2$, primary production in plant communities are highly sensitive to atmospheric $CO_2$ concentrations[68,86,20,70]. Concentrations of $CO_2$ in the atmosphere have already increased from 350 to 370 parts per million in the last 20 years and are predicted to approximately double by 2080, with potentially profound effects on physiological and ecological processes in all plant communities.

There are few studies of the impacts of elevated $CO_2$ on mangroves. Only two studies, Farnsworth et al.[86] and Ball et al.[20] directly address this issue. In other higher plants, photosynthesis and growth is often enhanced at doubled atmospheric $CO_2$ concentrations, however the level of enhancement is dependent on other interacting environmental factors[69,138]. Growth enhancements are also attributed to declines in respiration under enhanced $CO_2$ concentrations that are in the order of approximately 20 percent[70]. In mangroves, elevated $CO_2$ conditions (twice ambient) had little effect on growth rates when growth was limited by salinity, but increased growth by up to 40 percent when growth was limited by humidity[20]. Faster growing, less salt tolerant species were more responsive to elevated $CO_2$ conditions, having enhanced growth rates compared to slower growing more salt tolerant species. This may suggest that upstream productivity and expansion of mangroves into fresh and brackish wetlands could occur at an accelerating pace.

Another common plant adaptation to elevated $CO_2$ concentrations is decreased nitrogen invested in leaves and a concomitant increase in the carbon:nitrogen ratio of plant tissues. Changes in the stoichiometry of carbon and nutrients in plant tissue will have flow on effects to consumers[175] and on decomposition processes[28]. Elevated $CO_2$ concentrations are therefore likely to impact food webs, carbon and nutrient cycling and the quality of exports from mangroves.

The available data suggest that under future elevated $CO_2$ primary production is likely to be enhanced, although not uniformly over the range of mangrove environments within the GBR. Increases in $CO_2$ concentrations may partially reduce the negative effects of reduced humidity and rainfall expected where temperatures increase in northern regions. Increasing levels of $CO_2$ may also change patterns of species dominance and accelerate mangrove encroachment into adjacent brackish and freshwater wetlands.

### 9.2.4 Changes in UV

Ultraviolet B (UVB) radiation is damaging to proteins and nucleotides and thus enhanced levels can lead to damage in plant tissues. Mangroves have a suite of pigments that absorb UVB radiation within their leaves likely due to their evolution in tropical latitudes where UVB radiation levels are high[113]. Impacts of enhanced UVB radiation are most likely to affect plants in temperate regions. Anticipated effects include small reductions in photosynthetic rates and altered morphology[44]. Although, UVB radiation is predicted to have a large effect on subtidal primary producers, effect on intertidal plants is not expected to be large[66].

### 9.2.5 Sea level rise

#### *9.2.5.1 Exposure and sensitivity – sea level rise*

Mangroves, salt marshes and salt flats are within the intertidal zone of low energy coasts and are thus highly sensitive to rising sea level. During past sea level rise mangroves were unable to withstand rates of sea level rise that exceeded 1.4 mm per year (Bermuda[79]). However, sea level rise thresholds for mangrove loss and for changes to intertidal wetland communities will vary depending on a range of interacting factors, including geomorphological setting, tidal range, accretion (eg from sediment inputs), subsidence[79,39], tree growth rates and species composition[39,42,109]. Current rates of sea level rise

in the GBR are 2.9 mm per year (Lough chapter 2) but there is no evidence to suggest that fringing mangroves are declining. In contrast, increases in mangrove cover through recruitment into landward salt marshes have been documented in southern Australia[157,152] and encroachment of mangroves into fresh water wetlands has been observed in northern Australia[14].

Geomorphological setting and tidal regimes of mangrove habitats and associated wetlands will strongly influence responses to sea level rise[187,184,158]. Typological classifications of geomorphology[186,158,103] underlie most models of the effects of sea level rise on wetlands. For example, the classification of river delta, lagoon or estuary describes both the landform and summarises a range of landscape processes including sediment supply, wave energy and water flow rates. Thus, geomorphological classification systems combined with other modelling tools have been commonly used for the assessment of vulnerability of coastal environments to sea level rise[132,162,131].

Tidal ranges are also anticipated to have a large impact on wetland responses to sea level rise, with greater exposure expected in areas with smaller tidal ranges compared to those with larger tidal ranges[158,188] (Figure 9.1). In the GBR, mean tidal range varies widely from 1.7 to 6.2 metres (Figure 9.2). Recent models to assess the vulnerability of wetlands to sea level rise used tidal range as a key parameter, with vulnerability directly proportional to the inverse of tidal range[132] (Figure 9.3). For example, the northern GBR with its relatively low tidal range has a greater risk of wetland loss with sea level rise compared to the southern GBR that has a higher tidal range.

### *9.2.5.3 Impacts – sea level rise*

Many of the mangrove areas of the GBR region are associated with broad, flat coastal plains that often have large areas of intertidal salt flat and high intertidal salt marsh (eg Fitsroy River[71]). In previous high sea level stands salt flats and salt marsh areas were covered in mangrove forests, in what Woodroffe[186,187] has called the ‘big swamp’ phase of estuary development. Sea level in the GBR region has dropped by approximately one metre in the last 6000 years resulting in mangrove forests that currently occupy the edges of coastal plains with the development of salt flats and salt marshes behind them (landward), and in areas of high rainfall, the development of extensive fresh water marshes. With sea level rise landward migration of mangroves into salt marshes, fresh water wetlands or agricultural lands (where there are no significant human barriers to prevent this) is highly probable. Landward migration is known to have occurred in the past[84,79,188], and in some areas in Australia, and globally, is already occurring (eg King Sound in northwest Western Australia[158]; Mary River, Northern Territory[14]; southern Australian salt marshes[157,152]), resulting in significant changes in diversity and ecosystem function, often necessitating changes in human utilisation of the coast[c,77,105,106,131].

Although changes are anticipated in vegetation structure and coverage of intertidal wetlands with sea level rise, understanding of the functional consequences of these changes remains mainly qualitative. The impacts of sea level rise on tidal wetland fauna, sediment trapping, nutrient and carbon fluxes are currently not known with any certainty. Using data from Table 9.3, and physical parameters available from the audit of Australian estuaries database we provide a preliminary assessment of the impacts of sea level rise on some of the ecosystem services provided by mangroves and associated wetlands

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[c] Millenium Ecosystem Assessment 2005. www.millenniumassessment.org/en/index.aspx.

(Table 9.4). This estimation of impact is based on topographic proxies, for example, a high ratio of the area of salt marsh to mangrove is indicative of a gently sloping coastal plain, and tidal range. This is a simplification that does not account for human activities that influence wetland plant distributions (eg barriers to landward migrations and changes in sediment dynamics and nutrient enrichment).

***Figure 9.1*** *Variation in tidal range over the GBR*

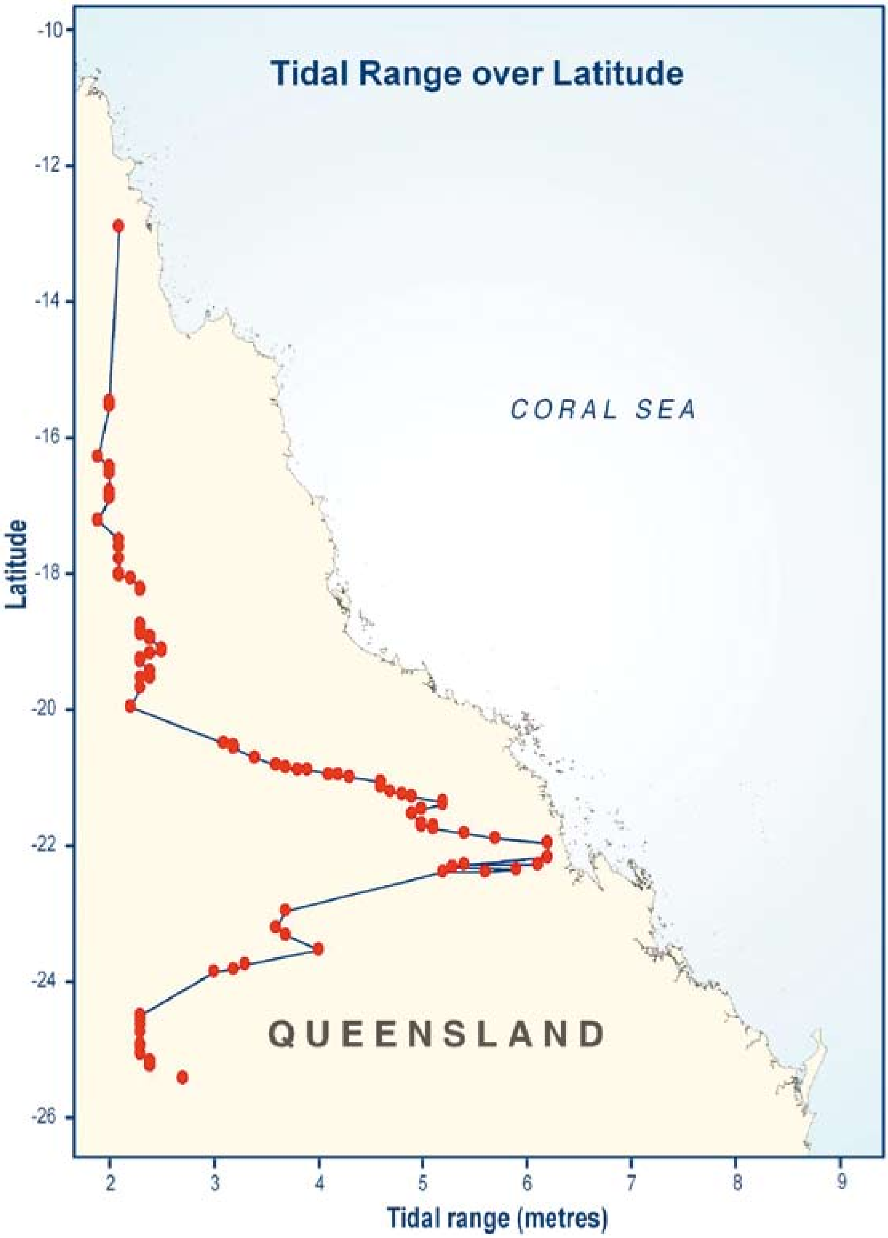

***Figure 9.2*** *Model indicationg the processes influencing vertical accretion in mangrove ecosystems (Adapted from Cahoon et al. 1999 by Diane Kleine)*

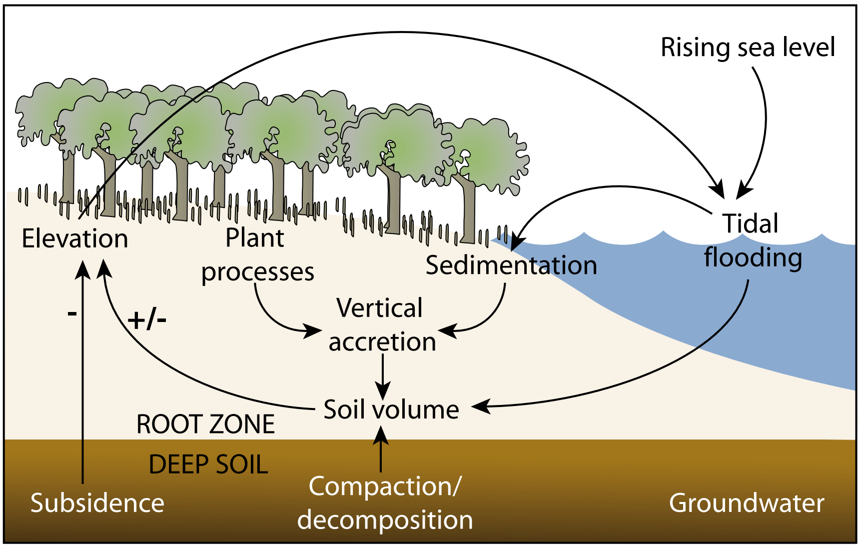

***Figure 9.3*** *Effects of tidal range on the proportion of mangroves affected by rising sea level. With similar bathymetry a greater proportion of mangrove forest will be lost in settings with low (microtidal) compared to high (macrotidal) tidal ranges*

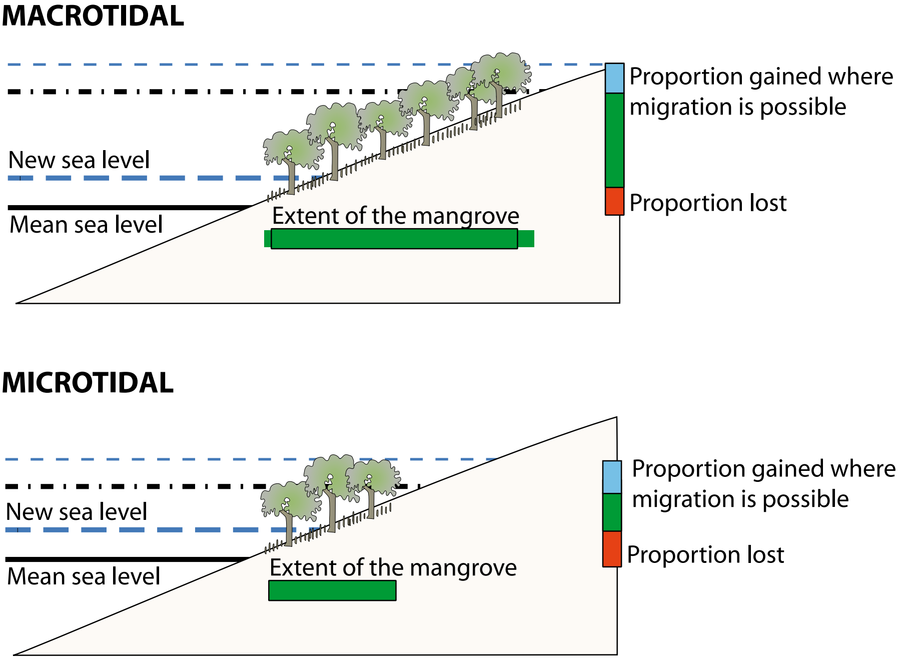

***Table 9.4*** *Projected changes in estuaries with sea level rise exceeding vertical accretion (no changes in rainfall, temperature or storms are considered)**

| **Mangrove: tidal flat+salt marsh area (km²)** | **Tidal range**** | **Exemplary estuary** | **Vertical migration possible** | **Projected change in mangrove area** | **Sediment trapping** | **Carbon and nutrient retention** | **Flora and Fauna** |
|---|---|---|---|---|---|---|---|
| Greater than 20 | Low | Johnstone | No | – | Reduced through time | Decreased as mangrove sediments eroded | Reduction in diversity of high intertidal fauna |
| Greater than 20 | High | Pioneer | No | – | Reduced through time | Decreased as mangrove sediments eroded | Reduction in diversity of high intertidal fauna |
| 1 to 2 | Low | Burdekin | Yes – but reduced through time | + | Same or increase through time | Same – increased though time | Loss of salt marsh flora and fauna, increase in mangrove species |
| 1 to 2 | High | Sarina Inlet | Yes – but reduced through time | ++ | Same or increase through time | Same – increased though time | Loss of salt marsh flora and fauna, increase in mangrove species |
| Greater than 0.5 | Low | Bohle | Yes | ++ | Same or increase through time | Increased though time | Loss of salt marsh flora and fauna, increase in mangrove species |
| Greater than 0.5 | High | Fitsroy | Yes | ++ | Same or increase through time | Increased though time | Loss of salt marsh flora and fauna, increase in mangrove species |

* The ratio of mangrove:salt marsh+salt flat vegetation was obtained from www.ozestuaries.com

** Low less than 2.5 metres, High greater than 2.5 metres

### *9.2.5.4 Adaptive capacity – sea level rise*

Mangrove forests and other intertidal wetlands may adapt to rising sea level and remain stable if the rate of vertical accretion of the soil surface of the wetland equals or exceeds the rate of sea level rise[39,126]. This simple idea underpins many of the current models used to assess wetland stability with rising sea level (eg Nicholls et al.[132], Simas et al.[163], Nicholls[131]). Wetland soil surface elevation and its response to sea level are influenced by a suite of interacting processes and feedback mechanisms (Figure 9.3) that occur on both the surface and subsurface (Table 9.5). Elevation of the wetland soil surface is directly influenced by soil volume, which is related to several interrelated processes. Tidal floodwaters deliver sediments to wetlands, where aerial roots and pneumatophores of mangroves enhance sediment deposition, adding to soil volume[109]. In addition, soil volume is related in part to soil organic matter accumulation, which is the net result of root growth (positive soil volume) and root decomposition (negative soil volume)[37,42,43]. Groundwater drainage and storage result in shrinking and swelling of soils (negative and positive soil volume)[182], and soil compaction (reduced soil volume) also influences soil elevation. As soil elevation increases the hydroperiod, which is the frequency, depth, and duration of tidal flooding, decreases (negative feedback)[38]. When sea level rises, hydroperiod increases. So as long as soil elevation gain matches sea level rise, the wetland will maintain the same relative elevation within the tidal frame, migrating upslope if need be.

***Table 9.5*** *Factors affecting the soil surface elevation of wetlands and wetland stability*

| **Surface processes** | **Impact** | **Interacting factors** |
|---|---|---|
| Sedimentation | Positive | Rainfall, river flows, sediment availability (catchment land use) |
| **Subsurface processes** | | |
| Root growth | Positive (soil volume and sediment trapping and binding) | Factors that affect productivity: Nutrient enrichment, elevated $CO_2$, humidity, rainfall, sedimentation |
| Decomposition | Negative | Dependent on sediment type, species, tidal regime |
| Deep soil layer compaction/subsidence | Negative | Groundwater, tectonic activity |
| Groundwater inputs | Positive/negative | Rainfall, tidal amplitude |

This model (Figure 9.3) and the instrumentation devised to test the model, the rod surface elevation table (RSET)[40,41] have been used to understand the vulnerability of wetlands to sea level rise by describing the trajectory of the elevation of coastal wetlands in response to a range of environmental conditions. In mangrove-salt marsh ecotones in southeastern Australia RSETs indicate that mangroves are invading salt marshes in the region because of subsidence of the soil surface due to reductions in groundwater inputs associated with El Niño cycles[151,152]. Subsidence increases tidal inundation, which favours the recruitment and growth of mangroves. Over the range of sites assessed by Rogers et al., sedimentation was a significant process in maintaining soil surface elevation in some wetlands but only accounted for 50 percent of variation in surface elevation. This result underscores the importance of other surface and subsurface processes in the maintenance of soil surface elevation and thus responses to sea level rise[151,152,43]. Using RSETs Cahoon et al.[43] observed subsidence of 37 mm per year in highly organic mangrove soils in Honduras after a severe hurricane damaged the forest, demonstrating the importance of tree growth for the maintenance of soil elevation. In both salt marshes and mangroves, nutrient enrichment has been observed to enhance vertical accretion and surface elevation through deposition of roots[126,117]. In mangroves in Micronesia, data from RSETs indicate pnuemataphore type (ie mangrove species) plays an important role in the maintenance of surface elevation through differential abilities of species to promote sedimentation and sediment binding[109].

### *9.2.5.5 Vulnerability and thresholds – sea level rise*

Of the 97 estuaries within the GBR that have been surveyed[d], the ratio of salt marsh-salt flat to mangrove exceeds one in 30 percent of estuaries (Figure 9.4). The high proportion of salt marsh-salt flat:mangrove indicates there is a gently sloping coastal plain that is currently infrequently inundated but which may allow for a significant expansion of mangroves landward with sea level rise. Conversely, in areas of the GBR where mangrove to salt marsh ratios are high (Figure 9.5), due to steep coastal topography or to modifications by humans where barriers to landward migration of the intertidal have been created[61,110], mangrove cover is likely to be reduced with sea level rise. Reductions in intertidal wetland cover are particularly likely where there are low rates of vertical accretion and the soil surface of the wetland cannot keep up with sea level, due to some combination of low sediment availability, low root growth rates or subsurface subsidence.

The large range in tidal amplitude over the GBR also suggests that the vulnerability of mangroves to sea level rise will be variable along the coast. Following the approach of Semeniuk[158] and Woodroffe[188], mangroves and wetlands in the high tidal range areas of the GBR (latitudes greater than 20° S) should be less vulnerable to sea level rise than those in areas with low tidal ranges (latitudes less than 20° S). Geomorphological settings of highest vulnerability include low wooded islands that have a relatively low tidal range, no possibility of landward migration and limited sediment inputs. Nicholls et al.[132] defined a dimensionless relative sea level rise ($\text{RSLR}^* = \text{RSLS}^{e}/\text{tidal range}$) with a critical value ($\text{RSRL}^*_{\text{crit}}$) above which wetlands will be lost unless landward migration occurs. Data from the Caribbean, which is microtidal, suggests that $\text{RSLR}^*_{\text{crit}}$ ranges between 0.18 and 0.5. Estimates of RSLR* from the GBR, using current rates of sea level rise in the GBR (2.9 mm per year) ranges between 0.4 at sites with high tidal ranges and up to 1.6 at sites with low tidal ranges. The threshold, $\text{RSLR}^*_{\text{crit}}$ for the GBR is yet to be established, but it could be a useful tool for developing quantitative assessments of vulnerability of GBR wetlands to sea level rise.

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[d] www.ozesturies.org

[e] Relative Sea Level State

***Figure 9.4*** *Ratio of salt marsh to mangrove area in the GBR*

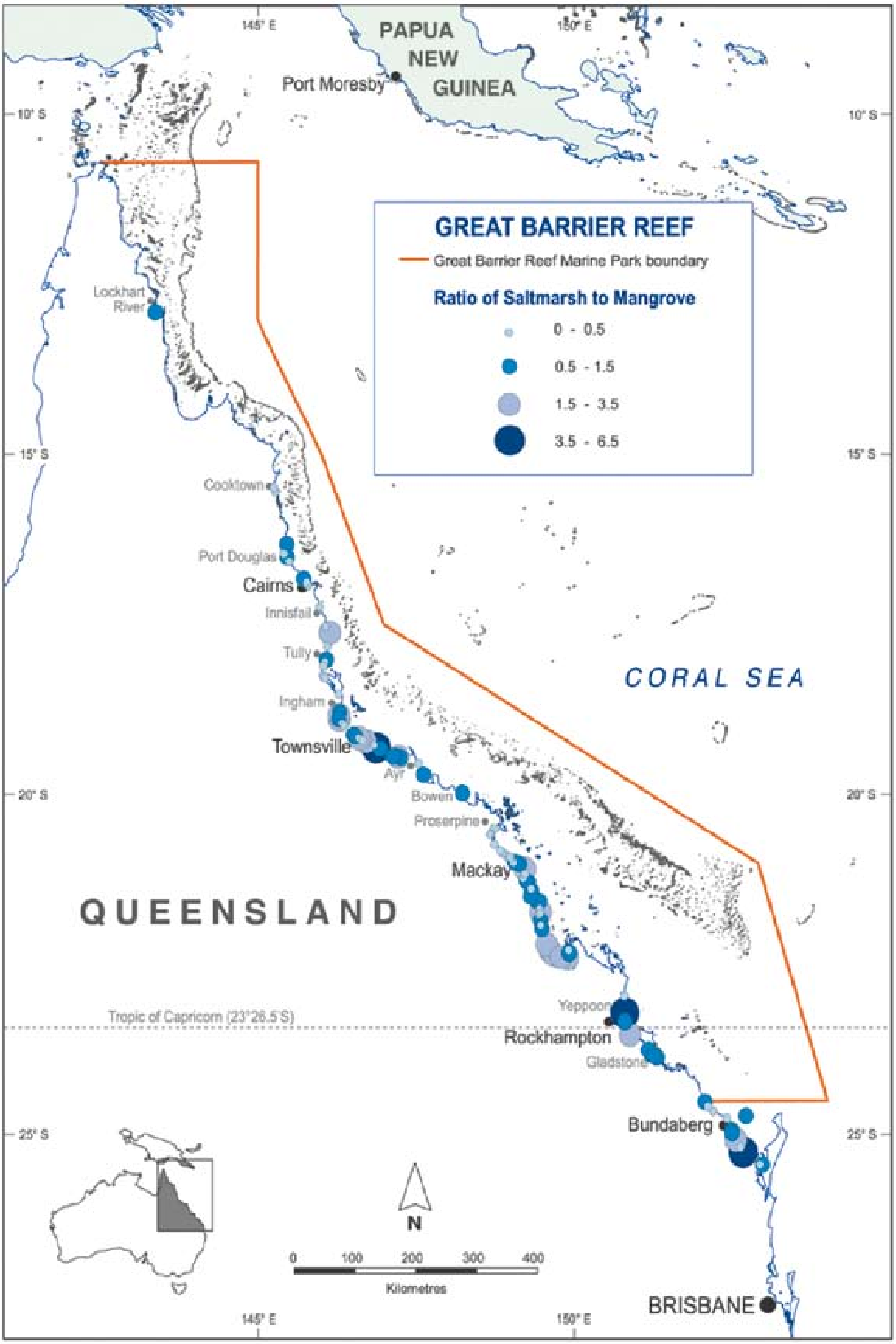
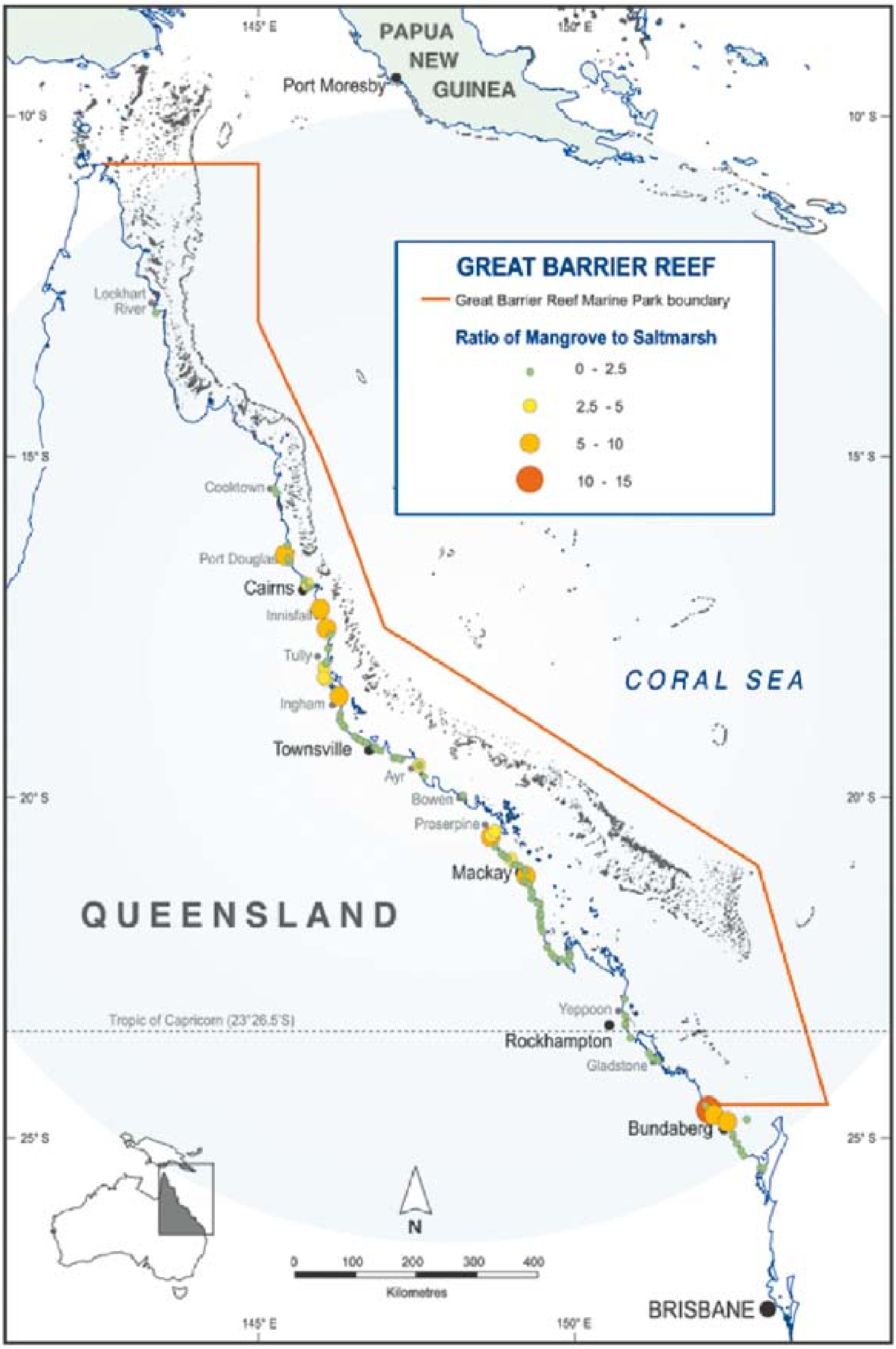


***Figure 9.5*** *Ratio of mangrove to salt marsh in the GBR*



## 9.2.6 Physical disturbance – tropical storms

Mangroves have an important role in protecting coasts from storm and tsunami damage[169,119,123,60,63]. Most tropical ports in Australia recommend small craft use mangroves as protection in the event of cyclones. For example, from the Port Douglas cyclone protection plan ‘The creeks and waterways off Dicksons Inlet, within the mangrove areas, offer the best shelter/protection for small vessels’[f]. Storms can have a large impact on mangroves, with catastrophic destruction being observed in the Caribbean and Bangladesh[169,120,42], often with very slow recovery[161,136], or none at all[42]. Intense storms can strongly influence surface elevation of wetlands through erosion, deposition and subsurface processes that can subsequently influence rates of recovery[36]. Quantitative data from Australia on impacts of cyclones on mangroves, and their recovery are rare[24,189].

Data from the Caribbean indicate mangroves can recover from severe storm damage providing patches of reproductive trees remain, and hydrology and sediments are not altered to an extent where reestablishment is prevented[169,80,161]. Tree species differ in their response to cyclones, with species from the Rhisophoraceae being particularly vulnerable as they are unable to resprout[16]. The effects of cyclones on fauna associated with mangroves in Australia are not known, but loss of mangroves from human disturbances in Kenya and Malaysia resulted in declines in diversity and abundance of fauna (reviewed in Manson et al.[118]).

## 9.2.7 Rainfall and river flood plumes

Changes in rainfall will have a major effect on intertidal wetlands of the GBR. The predicted changes in rainfall with climate change on the GBR are complex, with increases in rainfall predicted in some regions and decreases in others. There are also predicted to be increases in the intensity of rainfall events that are likely to influence erosion and other processes in catchments of the GBR (Lough chapter 2) having flow on effects on intertidal wetlands.

Rainfall influences species composition, diversity and productivity of intertidal wetlands. Freshwater inputs to intertidal wetlands reduce salinity, increase the water content of soils and deliver sediments and nutrients creating conditions that are favourable for plant physiological function[168,18]. Rainfall also influences groundwater inputs, which can lead to the maintenance of soil surface elevation through subsurface swelling of soils[182,151]. Connectivity of habitats with flushing accumulated material from salt flats to mangroves and nearshore waters is also strongly influenced by rainfall[141] (see chapter 19).

In the GBR and other locations, sediment delivery to the estuary co-varies with rainfall[65] and increases with human development of the catchment[94]. Sedimentation increases surface elevation of wetland soils relative to sea level as well as increasing habitat for mangrove colonisation (eg Trinity Inlet, Cairns[71,74]). In addition to increasing soil surface elevation, delivery of sediments has a direct positive effect on plant growth[135,104,78,114], although it can lead to reduced diversity of fauna[78] and tree mortality if sedimentation is excessive[80]. Increases in frequency of intense rainfall events combined with land use change in catchments will increase sedimentation which will increase the availability of suitable mangrove habitat and enhance mangrove growth[114], however excessive sedimentation events could result in forest losses[80].

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[f] http://www.marinamiragepd.com.au/cyclones.htm

Where rainfall is reduced, productivity, diversity and the area of wetlands will decline with possible increases in the area of salt flats[168]. Reduced rainfall will lead to reductions in sedimentation. Within the GBR, sedimentation in mangroves has been observed to vary between -11 mm per year (erosion) to 10 mm per year[95,26,171,34]. At the higher end, sedimentation is higher than projected sea level rise, but there is not sufficient data to determine what levels of sedimentation in mangroves occur over most of the GBR. In a study of sedimentation in southern Australia, sedimentation was higher in mangroves compared to salt marsh (approximately 5 mm per year in mangroves and 2.5 mm per year in salt marsh[150]). Sedimentation increased linearly with tidal range (sedimentation in mm per year = -4 + 3.7 x tidal range in metres). Extrapolation using the tidal range of the GBR, and assuming a similar sediment supply suggests sedimentation could vary from 1.6 to 2.8 mm per year, which is at the low end of the published range and is slightly lower than current rates of sea level rise. Thus areas of the GBR with low tidal ranges, low rainfall and limited sediment supply are more likely to experience retreat of seaward fringing mangroves with sea level rise compared to those areas with high tidal range, high rainfall and an ample sediment supply, which are conditions where mangrove expansion is likely to occur.

## 9.3 Threats to resilience

Overall our analysis leads us to predict that the total area of mangrove forest in the GBR is likely to increase with sea level rise, particularly as sedimentation, elevated $CO_2$, enhanced rainfall and nutrient enrichment have a positive influence on mangrove growth. Mangroves will migrate landward and will reoccupy salt marsh and other wetlands inland of current mangrove distributions, as has occurred in the past[186,188]. Large gains in mangrove area, possibly at the expense of salt marsh and salt flats, may be expected in the arid tropics, particularly in estuaries surrounding Townsville and Rockhampton (Figure 9.4). Increases are particularly likely if high sediment deposition rates due to land-use change in the catchments are sustained or increased with altered rainfall patterns, creating new habitat for mangrove colonisation. Additionally, high sedimentation and enhanced mangrove growth with elevated $CO_2$ and anthropogenic nutrient enrichment may enable mangrove fringes to maintain their position relative to sea level rise, reducing losses of seaward fringing forests due to submergence.

Losses in mangrove area may occur if high temperatures and aridity depress mangrove productivity and if sediment delivery is reduced. Pollution and storm damage could accentuate these losses[76]. Under scenarios of negative human influence (eg pollution and impoundment by building of barriers), reductions of fringing mangroves may be substantial, and forests establishing landward may have reduced productivity.

The largest threat to the resilience of intertidal wetlands with climate change is the presence of barriers that will prevent landward migration of intertidal wetland communities. Barriers to landward migration of intertidal communities can be imposed by natural features (eg steep slopes), but urban, agricultural and other human developments that build berms, bunds, seawalls and roads on coastal plains impose significant threats to resilience of mangroves, salt marsh and salt flats with sea level rise. Barriers also reduce connectivity between habitats and overall productivity (see chapter 19). Landward barriers to wetland migration will have particularly negative consequences for salt marsh and salt flat communities that are compressed between human imposed landward barriers and encroaching mangroves[157,3].

Reducing threats to resilience requires determining where barriers will lead to unacceptable changes in mangrove, salt marsh or salt flat communities followed by removal of barriers to landward migration. Areas of greatest concern are those that are highly developed (eg Cairns region) and which also have a relatively low tidal range and a high mangrove:salt marsh ratio. Additionally, where sediment and freshwater inputs (rivers and groundwater) are reduced, barriers to landward migration will have a greater negative impact on the intertidal wetlands of the GBR.

## 9.4 Summary and recommendations

### 9.4.1 Major vulnerabilities to climate change

Mangroves, salt marshes and salt flats are particularly vulnerable to sea level rise. Increases in sea level should lead to an increase in the area of mangroves, and migration of mangroves, salt marsh and salt flats upslope. This scenario is likely in areas of the GBR with high tidal ranges, where rainfall is predicted to increase and where there are no barriers to landward migration. Expansion of mangroves may be further enhanced with elevated $CO_2$, nutrient enrichment and warmer winter temperatures at southern latitudes. Reductions in area of mangroves, salt marsh and salt flats will occur in response to sea level rise if the soil surface elevation of the wetlands cannot keep pace with rising sea level. This is most likely to occur in areas with low tidal ranges, where rainfall is reduced, where sediment inputs are not sufficient to contribute to the maintenance of surface elevation and where groundwater depletion leads to subsidence of sediments. Additionally high temperatures, low humidity and more severe storms could also lead to reduced productivity, subsidence and erosion. The presence of human created barriers to landward migration of wetlands will have a significant negative impact on intertidal wetland cover.

Reductions in mangrove, salt marsh and salt flat area will decrease the level of ecosystem services they provide (Table 9.3), but we do not know quantitatively how reductions in area of wetland will equate to reductions in ecosystem services. This is partly because not all parts of the intertidal zone provide equivalent services, eg seaward fringes of mangroves provide disproportional level of sediment trapping compared to landward forests[95]. However, we expect that loss of diversity of flora and fauna is likely with reductions in salt marsh area and encroachment of mangroves into fresh water marshes. Sediment trapping, carbon sequestration and nutrient cycling will be reduced with declines in wetland cover resulting in higher turbidity and higher nutrient loading in nearshore waters. Carbon and nutrient subsidies to nearshore waters would also be reduced resulting in reductions in the productivity of nearshore food webs (see chapter 19).

### 9.4.2 Potential management responses

Increasing the resilience of GBR intertidal wetland habitats to climate change firstly requires attention to management actions that focus on responses to sea level rise. Particular attention should be focused on accommodating the landward migration of mangroves, salt marshes and salt flats. Management will be challenging. There are a wide range of current users of low elevation lands that will be directly affected by sea level rise, including farmers, large infrastructure (eg airports and ports), urban dwellers and indigenous communities. Additionally there are groups who benefit both directly (eg fishers) and indirectly (eg water quality) from wetland ecosystem services. Currently no single regulatory body has a mandate to manage the terrestrial-marine interface or the issues arising from the competing interests of different interest groups. Given the magnitude of the expected sea level rise in the next century (Lough chapter 2), changes in the landward extent of the intertidal, the high value of the ecosystem services wetlands provide and the high value of coastal property to a range of stakeholders, the development of an organisation that can oversee management of current and future intertidal regions may be practical and desirable. Management responses should also include:

1. Quantitative assessment of lands that will become intertidal by 2080. Digital elevation models of estuaries are needed to augment and improve the OzEstuaries database.
2. Development of management processes that would a) create buffers around wetlands to increase resilience, and b) assist in relinquishing lands to accommodate landward migration of intertidal habitats.
3. Improving the knowledge of how wetlands are changing with rising sea level and with other environmental changes. This could be achieved through historical assessments (eg Duke et al.[75]) and by measuring current rates of surface elevation change relative to sea level rise in different wetland settings and under a range of environmental conditions.
4. Development of a management framework to aid decisions on whether and which wetlands should be conserved or restored in anticipation of rising sea level. Decision tools should incorporate valuation of diversity and ecosystem function and knowledge of the effects of extreme events (eg storms, pollution) on wetlands. The management framework could include consideration of the costs of restoration or defence against tidal incursions versus gains from sustaining current use and potential gains (eg fisheries habitat and carbon credits) from allowing mangrove and salt marsh landward migration.

### 9.4.3 Further research

The vulnerability assessment presented here is qualitative, but the information available for the GBR is extensive compared with many other tropical regions of the world. There are significant gaps in our knowledge that once filled would allow a quantitative assessment of the effects of climate change on mangroves and associated wetlands, knowledge that would aid in the development of much needed tools for managing wetlands in the GBR and elsewhere. Critical information gaps that need to be addressed include:

1. A capacity to model the effects of sea level rise on intertidal wetlands in detail in many areas of the GBR. Detailed digital elevation models of mangrove, salt marsh, salt flats and coastal plains and fine scale classification of the coast into typological units based on geomorphological characteristics would aid the development of models. Additionally more informed linkages between geomorphological classifications and ecological and physical processes would facilitate prediction of the effects of sea level rise on ecosystem services.
2. Rod surface elevation table installations that can measure the trajectory of wetland surface elevation relative to rising sea level and provide an experimental framework to link processes influencing surface elevation (eg variation in rainfall, nutrient enrichment and sedimentation) to wetland stability.

3. Knowledge of current sedimentation rates in mangroves and other wetlands (and differences from historical sedimentation rates) and the importance of sedimentation to wetland stability.
4. Understanding the magnitude of ground water inputs into mangroves and other tidal wetlands and the importance of this process to primary production, diversity and maintenance of surface elevation.
5. Improved knowledge of faunal responses to changing intertidal wetland plant species composition, changes in extent and connectivity of habitats and changes in productivity.
6. An enhanced understanding of how climate change factors interact with other human induced changes (eg nutrient enrichment) to influence productivity and stability.
7. Knowledge of the sensitivity of carbon and nutrient storage and cycling in intertidal wetland soils to climate change drivers (atmospheric changes, temperature and sea level rise) and how this varies spatially within GBR wetlands.
8. Quantitative understanding of the impacts of cyclones on intertidal wetlands, rates of recovery and interactions with other factors (eg sea level rise).
9. Development of decision tools for management of the GBR that incorporate biological, social and economic factors.

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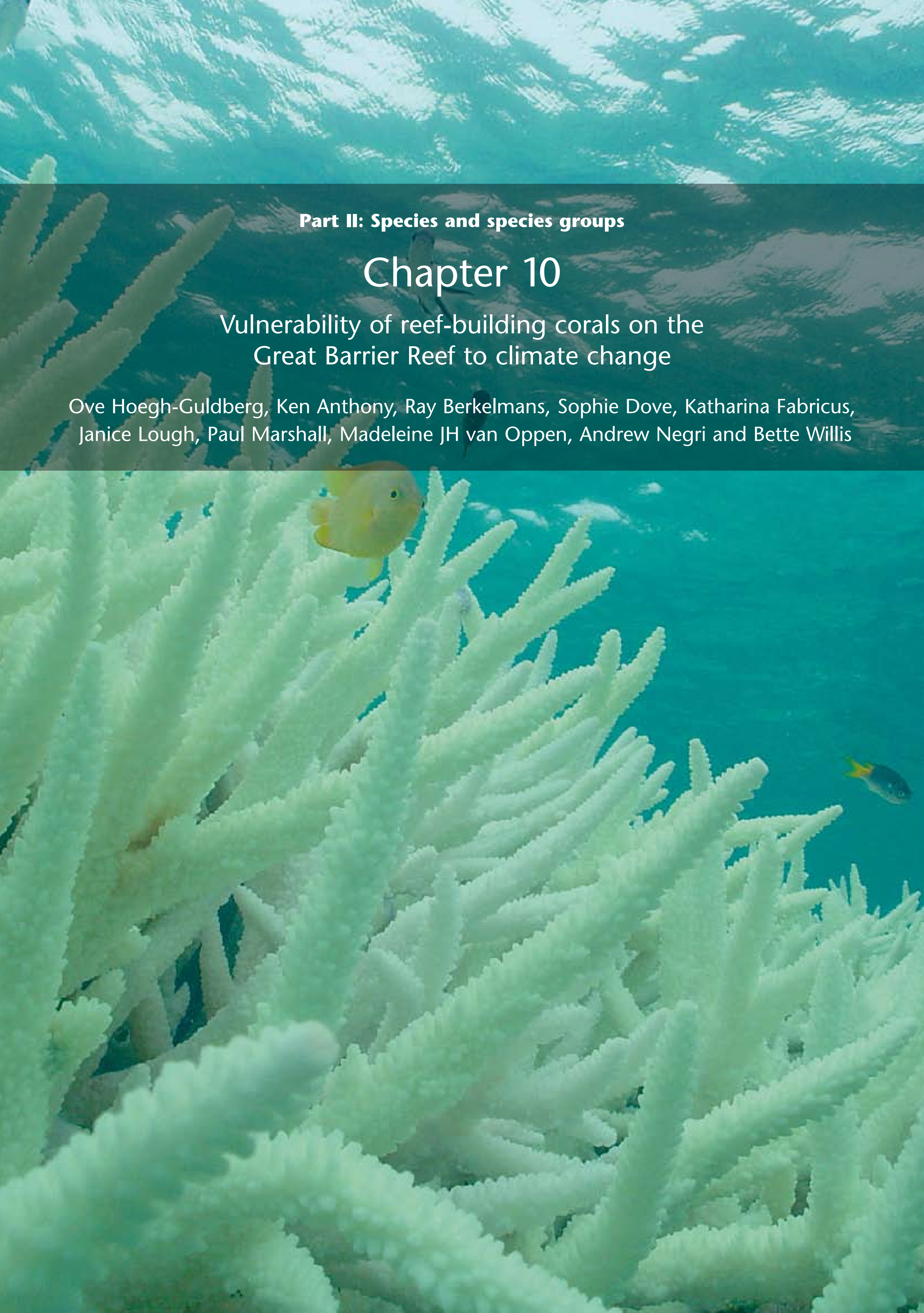

Part II: Species and species groups

# Chapter 10

## Vulnerability of reef-building corals on the Great Barrier Reef to climate change

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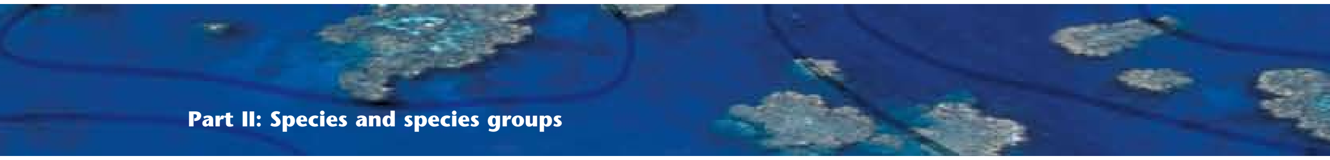

## 10.1 Introduction

### 10.1.1 Reef-building corals

Reef-building corals (Order Scleractinia Class Anthozoa) form extensive skeletons of calcium carbonate (limestone), depositing enough material over time to form vast reef structures that may be easily seen from space. The majority of reef-building corals are hard (stony) scleractinian corals. Many octocorals (especially soft corals in the family Alcyoniidae and the blue coral *Heliopora*) and some hydrozoan corals (such as *Millepora*) also contribute to reef-building. Corals form the framework of reef structures, while other organisms such as calcareous algae (especially red coralline algae) play a key role in cementing and consolidating the reef framework. This chapter focuses on the vulnerability of reef-building corals to climate change. The implications of climate change for macroalgae are covered in chapter 7 and a broader treatment of reef processes is provided in chapter 17.

### 10.1.2 The role of reef-building corals in the GBR

Major coral reefs stretch along both coastlines of the Australian continent, from Frazer Island to Torres Strait on the east coast, and from the Houtman Abrolhos reefs across the northwest coast of Australia to the western edge of the Gulf of Carpentaria on the western side of Australia. These coral reefs show a tremendous variety of structures within this broad geographical range, from poorly developed reefs that fringe inshore regions to extensive carbonate barrier reefs offshore. At more southern locations, coral populations form important communities despite the fact that temperature, light and the concentration of carbonate ions are such that there is no net accumulation of calcium carbonate. These reefs are referred to as non-carbonate coral reefs. Australian coral reefs provide critical habitat for a diversity of fauna and flora that includes over 400 species of corals, 4000 species of molluscs and over 1500 species of fish. The role of coral reefs in underpinning coastal economies in Australia is becoming increasingly recognised with the pristine nature of coral reefs being identified as the key driver of an internationally focused tourism industry. The contribution that the Great Barrier Reef (GBR) tourism industry makes, as part of regional tourism, to the Australian economy is A$6.1 billion per annum[86,1].

### 10.1.3 Critical factors for coral survival

Corals have a symbiotic relationship with dinoflagellate protists (division Pyrrhophyta, class Dinophycaea, genus *Symbiodinium*), which are referred to loosely as zooxanthellae. The dinoflagellate cells of Symbiodinium exist within vacuoles in coral host cells, forming a close endosymbiotic mutualistic association. The dinoflagellates photosynthesise at rates similar to that of free-living dinoflagellate species but translocate up to 95 percent of the photosynthetic products to the host cell (reviewed in Muscatine[143]). The coral receives a range of products including sugars, amino acids and larger compounds such as lipids and small peptides. In return, the dinoflagellate symbionts gain access to a rich supply of inorganic nitrogen and phosphorus from the host, which supports the primary productivity of the dinoflagellate under the otherwise low-nutrient conditions typical of sub-tropical and tropical seas. The efficiencies of the internal recycling of nutrients with corals are considered to underpin their ability to build the vast reef structures found along tropical and sub-tropical coastlines.

Examination of the environmental conditions under which corals thrive today provides valuable insight into the sensitivity of corals to key environmental variables and to how they might respond under future climate change. Kleypas et al.[105] explored the environmental factors underpinning 6451 reef locations and identified several factors that were correlated with the distribution of coral reefs. In particular, they noted the strong correlation of carbonate reef systems with well-lit, warm (greater than 16°C) and saline (23 parts per thousand) waters with aragonite saturation states ranging from 3.28 to 4.06. Interestingly, coral reefs are found in a range of nutrient concentrations in contrast to common dogma that coral reefs are always found in low nutrient conditions. These conditions give us insight into the evolutionary limits of reef-building corals, which is important in understanding how corals might, or might not, be able to cope with the major environmental changes projected to occur over this century. This is particularly relevant to problems associated with the acidification of ocean waters caused by rising atmospheric carbon dioxide[94]. Under almost all future scenarios, changes in atmospheric carbon dioxide are likely to decrease the average aragonite saturation state of the world's oceans well below 3.0, the point at which most corals appear unable to form skeletons.

A great deal of research has been undertaken on the direct impacts of climate change on adult coral colonies. The effects on potentially sensitive reproductive processes, however, have received far less attention. Successful reproduction and recruitment is essential for ongoing survival of coral reefs, particularly following heavy disturbances such as bleaching, where recovery of coral abundance and diversity relies largely on recruitment by larvae or propagules from other coral communities[44]. Corals have two distinct strategies for reproduction: broadcast spawning of gametes and brooding of larvae[79]. The early life stages of corals (such as oocytes, sperm, larvae and recruits), as well as critical transitions in life history (fertilisation and larval settlement), may be just as susceptible to thermal stress as mature colonies.

There are many other factors that influence the survival of corals. Poor water quality, such as high nutrient levels and sedimentation rates, can have dramatic influences on corals and the reefs they build. Coral reefs change and diminish as they approach coastal areas typified by natural coastal runoff and flooding events[187]. In recent times, coastal development has increased the amount of sediment flowing off the land[132], adding agrichemicals and other pollutants. Decreasing light levels, increased sediment levels and increasing levels of pollutants can reduce coral growth and in some circumstances have removed coral communities from reefs altogether[188]. Storm frequency and intensity also influences coral reefs, through natural events that may remove corals temporarily from some areas. Natural disturbance events like storms are considered to play an important role in mediating the strong competitive forces that may end up excluding less competitive species.

Discussion of how environmental factors determine the distribution of reef-building corals is important basis from which to explore the vulnerability of reef-building corals and their dinoflagellate symbionts to climate change. The next section focuses on such vulnerability within the context of thresholds, specifically with respect to those factors that appear to play a key role in determining the distribution of corals. In addition to dealing with issues of stress exposure, the sensitivity and potential impacts of these factors will also be considered.

# 10.2 Vulnerability of corals to climate change

## 10.2.1 Changes in water temperature

### *10.2.1.1 Exposure – water temperature*

Average water temperatures of the GBR are now significantly warmer than at the end of the 19th century, 0.4°C warmer based on 30-year averages (Lough chapter 2). Rates of warming of Australia's tropical and sub-tropical waters are similar to that seen globally for tropical waters (+0.17°C from 1951 to 1990[126]). As with changes in global temperature, these changes are unprecedented in terms of rates of change seen over the past several hundred[128] if not several thousand years. Warming seas have pushed corals ever closer to their thermal maxima, with the result that warmer than average years (part of natural variability) now push corals beyond their thermal tolerance[82].

### *10.2.1.2 Sensitivity – water temperature*

The most dramatic manifestation of corals being pushed beyond their thermal tolerances is coral bleaching, which is a condition in which corals lose the brown pigmentation of their dinoflagellate symbionts. Coral bleaching is essentially a stress response in corals that arises as the intricate endosymbiosis between animal and single-celled plant begins to break down.

Corals will bleach in response to a range of conditions including high or low irradiance[186,201,88,71,121], elevated or reduced temperatures[97,98,40,88,76,169,90], reduced salinity[103], the presence of some toxins (eg cyanide[100], copper ions[99], herbicides[147] and microbial infection (eg Vibrio[110]). Bleaching in response to isolated and local-scale (1 to 500 metres squared) stresses has been reported for at least 70 years[201].

Sensitivity of corals to thermal stress can be highly variable between species[134,129,185], between populations within species[75,22,185] and at spatial scales ranging from centimetres to thousands of kilometres. Some of this variation in sensitivity in space may be due to environmental factors such as differential light regimes[40], water motion[144] and thermal micro-, meso- and macroclimates. However, a number of biological factors also play a significant role in the sensitivity of corals to temperature. The symbiont type associated with corals in particular has been shown to greatly influence thermal tolerance with so-called type D symbionts conferring an extra 1 to 1.5°C tolerance in *Acropora millepora* compared to type C2[22].

Thermal sensitivity at the coral species level is likely to be shaped in large part by host factors that govern which symbiont types form stable symbiosis with particular species, the strength of association under stressful conditions and the flexibility of the symbiosis. Some of the differential sensitivity to thermal stress among species and populations may be due to biochemical processes. For example, enzymes involved in antioxidant functions such as copper/zinc superoxide dismutase and manganese superoxide dismutase and molecular chaperones such as heat shock proteins Hsp60 and 70 and chlorophyll Hsp have been shown to play a role in the defence against thermal stress in either or both animal hosts and symbiotic algae[29]. Similarly, mycosporin-like amino acids produced by coral hosts have been shown to provide protection against damaging ultraviolet (UV) radiation during hot, still conditions[54,137]. The role of fluorescent pigments in the photo-protection of corals during bleaching is less clear. These pigments are more common in corals in high light environments, such as reef flats, and are clearly involved in shading corals and their symbionts from excessive light levels[51,167]. They are also a diverse group of pigments with a range of functions that do not necessarily include reduced

sensitivity to bleaching[50]. These protective and reparative mechanisms are also evident in coral eggs and larvae[139] and may influence differences in sensitivity to thermal stress between species and life history stages.

### *10.2.1.3 Impacts – water temperature*

Mass coral bleaching events are triggered by warmer than normal conditions, a strong relationship as seen by the fact that mass bleaching events can be predicted using simple sea surface temperature anomalies measured from satellites and time-integrated temperature curves[21,82]. Light is an important co factor. Corals that are shaded do not bleach as severely as those under normal irradiances[100,142,9] which is a consequence of the mechanism that involves an increase in the sensitivity of the symbionts to photoinhibition[100,82]. The water flow field also appears to be important[144,145] and can greatly impact the photosynthetic performance of zooxanthellae *in hospite*[184], with corals that are in still as well as warm and sunlit conditions experiencing the greatest coral bleaching. This experimental outcome supports some of the initial observations of coral bleaching, which coincided with the doldrums that are typical of El Nino years in some coral reef regions[74].

Coral bleaching is not always fatal, and the outcome for the coral is dependent on the level of stress. Bleached corals may recover their symbiotic dinoflagellate populations following a bleaching event if the stress conditions are mild and short-lived. It may take several months for the dinoflagellates to repopulate the tissues, a process that arises from populations of dinoflagellates remaining in the host tissues. Often corals that appear bleached have as many as 10,000 dinoflagellates per centimetre squared[88] which is two to three orders of magnitude less that than that seen in healthy corals but more than enough to initiate re-infection from within. Mortality of corals will occur if conditions are warmer for longer periods, most likely because the symbiosis reaches a critically low energy status as the symbiont population continues to decline[9]. In some cases, mortality will increase to include most corals growing within a population, reef or region[82].

Australia's coral reefs have bleached repeatedly over the past 30 years, with events occurring in 1980, 1982, 1983, 1987, 1992, 1994, 1998, 2002 and 2006[150,82,20,24]. Large sections of the GBR have bleached during these years, with impact measurements supporting the conclusion that events in 1998 and then 2002 were the worst on record. Fortunately, mortality rates have been relatively low because the conditions have not been as severe as in other parts of Australia and the world (eg western Indian Ocean in 1998, 46% mortality of corals[68]). Scott Reef in the northwest waters of Australia, for example, has not been so lucky. In 1998, a very warm core of water persisted above the oceanic, and normally well flushed, Scott Reef for several months. This resulted in almost total bleaching and mortality of corals down to 30 metres. Recent reports indicate that recovery of these reefs has been slow[140], with the percentage cover of corals still very low compared to that seen before 1997. Additional bleaching in 2003 and a category 4 cyclone in 2004 have removed further corals from the remaining populations.

Not all coral species are equally susceptible to thermal stress[87], a factor that may be important in shaping the structure of future coral reefs. Following the 1998 bleaching event on the GBR, Marshall and Baird[134] demonstrated that bleaching susceptibility varies dramatically among coral taxa on the GBR: acroporids and pocilloporids were severely affected (18 to 38% mortality), poritids and faviids were moderately affected and genera such as *Turbinaria* and *Galaxea* were largely unaffected.

Interestingly, this pattern is consistent with the general pattern of species distributions across the GBR lagoon, with acroporids and pocilloporids increasing in abundance towards offshore locations and *Turbinaria* and poritids (in particular *Goniopora*) often dominating inshore reefs[46] often characterised by higher temperatures[21] and high turbidity[6]. Tentatively, increased frequency and intensity of thermal anomalies on the scale of the GBR may push most species of acroporids and pocilloporids beyond their thermal niche boundaries (ie threshold for sustained growth, reproduction and survival). Mid-shelf reefs may experience the largest changes in community composition as intensified runoff scenarios due to stronger cyclones mean that these reefs may occasionally experience high-turbidity regimes reminiscent of inshore reefs today.

Where thermal stress has resulted in significant mortality, coral community composition has often also radically changed as a result of the variable sensitivity of different species to stress. In the Palm Island Group in the central GBR for example, declines in coral cover of between 10 and 80 percent after the 1998 bleaching event were largely due to loss of dominant *Acropora* spp.[20,176]. Some species such as *Acropora pulchra* suffered local extirpation and other species such as the fire coral *Millepora* spp survived only as a few colonies growing in deeper water. Macro-algae increased to become the dominant cover on some of these reefs thus bringing about a community phase shift. This is a familiar pattern of community change echoed in Indian Ocean and many other reef provinces around the world after the 1998 global bleaching episode[197].

Increased water temperatures have the potential to affect both the reproductive output of parental colonies and the success of early coral life stages. Photosynthetic products are critical to coral gametogenesis and larval production[160] and bleaching during the typical eight-month period of gamete development[79] may negatively affect reproduction. Bleaching prior to or during gametogenesis can result in low testes and egg numbers along with smaller than usual eggs[192] and incomplete gametogenesis[177]. *Acropora* spp. that were affected during the 1998 Okinawan bleaching event also exhibited reduced fertilization in laboratory experiments performed nine months later[151]. Soft corals bleached in the laboratory were affected in a similar way, exhibiting reduced fecundity and fertilization failure over two reproductive cycles[138]. Larvae from these bleached colonies were lower in lipids, proteins and carotenoids compared with unbleached individuals[139]. Coral reproduction can also be directly affected by increased water temperature, with laboratory experiments indicating incomplete fertilization and more rapid (but often abnormal) embryogenesis as temperatures increase[19,18,147]. High water temperature can negatively impact larval development rates and the symbiont density in zooxanthellate larvae[58] and the settlement and survival of azooxathellate larvae[18]. Interestingly, high water temperature in the Virgin Islands was shown to correlate with higher numbers of juvenile corals, but this was accompanied by greater mortality rates[57].

### *10.2.1.4 Adaptive capacity – water temperature*

The preceding discussion is built on the premise that the behaviour of corals to thermal stress does not change on the same time scale of anthropogenic climate change. In this regard, it is important to consider the potential for corals to acclimatise (a phenotypic change within the individual) or to adapt (a genetic response at the population level) to thermal stress. There is no doubt that corals, like other animals and plants, acclimatise to changes in their environment including seasonal temperature changes[27,66,39]. Berkelmans and Willis[23], for example, found that the winter maximum upper thermal limit for the ubiquitous coral *Pocillopora damicornis* was 1°C lower than the threshold for the same

species of coral in summer. Nakamura et al.[146] have made similar observations for corals on reefs in Okinawa. Acclimatisation in this regard can occur in a range of cellular mechanisms and at a series of time frames[39]. As with any physiological trait, however, there are limits to the extent to which organisms can acclimatise to environmental change. Berkelmans and Willis[23] observed that corals have some potential to acclimate to seasonal differences in temperature. However, they have little capacity to acclimate to temperatures greater than 2–3°C above mean summer maxima, at least in experimental heating trials[20]. The observation of increasing (as opposed to decreasing) mortality rates among coral communities over the past 25 years also suggests that acclimatisation by corals to higher temperatures in the summer may have already been largely exhausted[82,68,69].

One of the ways in which reef-building corals may be able to acclimatise is by changing a thermally sensitive *Symbiodinium* type for one that is more thermally tolerant, an idea first put forward by Buddemeier and Fautin[32] as the Adaptive Bleaching Hypothesis. There are various interpretations of this hypothesis, and there has been active discussion in the literature over its definitions and whether or not there are data to support the elements of the hypothesis[89]. As yet, there is no evidence of exogenous uptake of new symbiont types by adult scleractinian corals although Lewis and Coffroth[123] provided some evidence for exogenous uptake by adult octocoral colonies (note: problems with the contamination of controls in this study throws some doubt on the conclusions however).

There are, however, several examples of multi-cladal associations (coral hosts that contain more than one genetic variety of *Symbiodinium*) that shift the dominance of one genetic variety over another[15,179,178,22]. These shifts in dominant genotypes as a function of environmental conditions suggest that some genotypes may be more suited to new environmental conditions. For example, Berkelmans and van Oppen[22] provided experimental evidence that *Acropora millepora* corals with multi-cladal assemblages can change the dominant symbiont type from *Symbiodinium* type C2 to D and can increase their thermal tolerance as a result. This type of change is a form of acclimatisation, because it represents a shift in the dominance of dinoflagellates that have had a pre-existing endosymbiotic relationship rather than the evolution of new symbiotic associations and also because in most instances the changes on the dominant *Symbiodinium* are not passed on from one generation to the next.

A distinction is drawn between *shuffling* and *switching* of symbiont types where the mechanism of acclimatization is due to the flexibility of coral-*Symbiodinium symbiosis*. Shuffling is a quantitative (compositional) change in the relative abundance of symbionts within a colony whereas switching is a qualitative change involving symbionts acquired from the environment. The latter exogenous symbionts may represent types that are new to the colony but not the species, or may be truly novel to the host species. In the latter case, the term 'evolutionary switching' is appropriate. The latter is used to explain changes in the symbiont distribution within hosts in response to stress. Evolutionary switching, however, is considered an extremely rare event and hence is unlikely to play the ecological role that some authors have claimed (eg Baker[15]).

In addition to understanding the limits to the flexibility of coral-*Symbiodinium* symbioses relative to ecological timescales, there has been a growing interest in defining the functional nature of the differences between *Symbiodinium* genotypes. In this respect, the range of genotypes of *Symbiodinium* dinoflagellates that inhabit corals[181,182,16,125,164,117] is correlated in some instances with light, temperature and stress. Some genetic varieties such as clade D are clearly correlated with warmer and putatively more stressful habitats than most types of clade C[183,166,185]. Growth in corals is also clearly influenced by symbiont type. Little et al.[124] showed that juvenile *Acropora millepora* and *A. tenuis* corals grow faster with *Symbiodinium* clade C compared to those associating with clade D. These types of studies are important in that they explore the functional responses of *Symbiodinium* strains that are otherwise only distinguished by the non-coding segments of their genomes. Future studies need to focus on how the growth, reproduction, thermal tolerance and mortality of corals are influenced by the strain or sub-cladal level of symbiotic dinoflagellates that they contain.

### *10.2.1.5 Vulnerability and thresholds – water temperature*

Isolated examples of coral bleaching have been recorded for many years. Reports, however, of entire communities and reefs bleaching (otherwise known as mass coral bleaching) have only been reported in the scientific literature over the past 30 years. In these cases, coral bleaching may affect up to 100 percent of the reef-building corals in a community. The first examples of mass coral bleaching occur in the scientific literature in the early 1980s[200,72,150], and since that time, mass coral bleaching has increased in frequency, intensity and geographical extent[82].

Some of the most spectacular examples of how mass coral bleaching can eliminate corals from a reef or region occurred during the 1997–1998 global event. In this event, which began in late 1997 in the eastern Pacific and spread across the world by the end of 1998, coral reefs in most parts of the world experienced mass coral bleaching. Some reefs, however, experienced only mild effects of bleaching and recovered within a few months. Other reefs, however, experienced severe coral bleaching that was followed by mass mortality. In regions like the Seychelles, Maldives, Okinawa and Palau, mortality of corals reached over 80 percent[82,196,77]. Some of these sites have recovered significantly. It is important to note that some regions still have much less coral than they had before the 1998 bleaching event[69] and hence the term 'recovering' needs to be qualified in most if not all cases.

Elevated sea temperatures are the primary cause of mass coral bleaching – a fact that is extensively supported by field and laboratory studies[26,82,120]. These data highlight the existence of thermal thresholds that vary with geographic location, species, genotype, physical factors (eg light, salinity) and history[41,56,99,82,23,21,28]. Despite this secondary source of variability, satellite measurements of sea surface temperature anomalies can still be used to predict bleaching events several weeks in advance with greater than 90 percent accuracy at large scales[82,175]. There is considerable additional information that can be derived as to the severity of the outcome of thermal stress if the time-period of exposure above threshold levels for a coral reef is also considered. High resolution time-temperature curves developed from *in situ* temperature data after the 1998 bleaching event[21] proved highly effective in predicting bleaching on the GBR in 2002 and 2006. Similarly, the Degree Heating Week (DHW) index developed by Strong et al.[175] is the multiple of exposure intensity (degrees above the threshold) and time, and has been highly successful in predicting mass bleaching events[a]. In the 1997–1998 global bleaching event, for example, coral reefs that experienced Degree Heating Month (DHM; a variant on DHW) values of less than 1.5°C per month largely recovered while those that experienced DHM values of 3°C per month or more experienced large scale mortalities[83].

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[a] Hotspot program, coordinated by the National Oceanic and Atmospheric Administration, NOAA. http://orbit-net.nesdis.noaa.gov/orad/coral_bleaching_index.html

Projections of how changing sea temperatures will impact Australia's coral reefs reveal that sea temperature may soon exceed the thresholds for coral bleaching on a yearly basis[82,48,49]. Based on how corals respond to increased temperatures today, an increase of 2°C in the average sea temperature in tropical and subtropical Australia will lead to annual bleaching with up to 97 percent of reefs affected and will almost certainly result in regular large-scale mortality events[82,84,24]. This is confirmed if one integrates the DHW index of Strong et al.[175] into the projections of how communities of corals will respond to thermal stress events that are hotter and longer in the future. Most evidence indicates that, for the majority of corals, huge increases in mortality will almost certainly ensue[85].

Models of how the expected changes in mortality will impact the abundance of coral communities indicate that even small changes in mortality regime may lead to large changes in the distribution and abundance of corals on the GBR. These changes have been examined geographically on the GBR by Done et al.[48], who modelled the probability of mild to severe bleaching events, and how recovery of such aspects as the aesthetic appeal of coral reefs interact within mild and severe climate change scenarios. Done et al.[48] found that the return time of devastating mass coral bleaching events even under mild warming scenarios was such that the ability of coral reefs to recover and maintain significant coral communities was severely compromised. The conclusions of their study support those of Hoegh-Guldberg[82] and suggest that the deterioration of coral populations is highly likely under most of the scenarios examined by Done et al.[48]. The debatable issue of rapid genetic adaptation, which may modify some of the conclusions of these two studies, will be discussed presently.

Successful reproduction and recruitment is essential to ensure the long-term survival of coral reefs, particularly following heavy disturbances such as bleaching[44]. Reef-scale sub-lethal bleaching is likely to lead to the widespread failure of gametogenesis[117,192] and a subsequent reduction in the recovery disturbed reefs. This secondary impact may persist over several reproductive seasons and[138] as corals prioritise their energy balance towards colony repair and maintenance rather than reproduction. The only study to directly measure fecundity on GBR corals following bleaching documented widespread reductions in egg number and size across several *Acropora* and *Montipora* species[192]. Direct comparisons between the sensitivity of adult corals and their early life stages to thermal stress have not been made for GBR species. *Diploria strigosa* larvae from the Gulf of Mexico, however, exhibited reduced settlement and increased mortality following a weeks exposure to seawater temperatures of between 30°C and 32°C, just 1 to 3°C above the ambient seawater temperature of that region[18]. This result indicates that the early life histories of coral may be just as vulnerable to direct thermal stress as adult colonies, even in the absence of symbiotic dinoflagellates. The severity of response is likely to vary between species, and recruitment following bleaching events may be skewed towards those species that are more tolerant to bleaching, further accelerating phenotypic change across reefs.

### 10.2.2 Changes in light and ultraviolet radiation

Light is obviously of key importance to coral reefs as it drives photosynthesis and powers calcification providing both the organic matter and the calcium carbonate foundation that defines coral reefs. Photosynthesis is however a dangerous process in that it involves the capture of light energy by chlorophyll and other phytopigments and generates a flow of electrons at the same time as it generates oxygen ($O_2$), a ready acceptor for those electrons. The potential danger lies in the creation of singlet oxygen due to the interaction of chlorophylls that are unable to off-load their excitation energy with $O_2$, and the production of other forms of reactive oxygen species such as superoxide anions ($O_2^-$) as $O_2$ accepts electrons that are unable to be processed by electron transport to carbon dioxide ($CO_2$) fixation[148]. The wavelengths of light that drive photosynthesis (photosynthetically active radiation) overlap the visible range and hence the pigments that capture this energy are also visible to humans. Shorter, more energetic wavelengths, (300 to 400 nanometres) also make it through the earth's atmosphere and are referred to as ultra violet radiation (UVR). The dangerous consequences of UVR are well known, most notoriously through the accepted causal role UV plays in the formation of skin cancers. UVR leads to indirect damage through its interaction with photosensitisers like chlorophyll leading to lipid peroxidation and DNA strand breakage. UVR can also directly damage DNA leading to structural changes that inhibit DNA replication and protein synthesis. The presence of UVR however has also been associated with positive morphogenic responses that enable plants to deal with other frequently co-occurring environmental stresses[70].

Light reaching the earth surface is attenuated in the atmosphere. Ozone plays the major role in attenuating UVR, and clouds (water vapour), dust and gases significantly attenuate photosynthetically active radiation and infrared radiation. Observations of decreases, about 3 percent per decade, in the global ozone, and increases in atmospheric $CO_2$, leading to changes in weather patterns that have a potential to alter cloud patterns can therefore significantly affect the intensity and quality of light attaining the earth's surface.

#### 10.2.2.1 Exposure – light and ultraviolet radiation

All reefs witness variability in light associated with diurnal patterns and differential cloud cover. At low latitudes, reefs are additionally affected by seasonal variability in light intensity. The water column attenuates light exponentially both by absorbing and scattering photons resulting not only in a reduction in the intensity of light with depth but also a change in quality due to the preferential absorption and scattering of red and infra-red photons. Even in crystal clear tropical waters, most of the red photons are absorbed within the first few meters of the water column with the implication that shallow water corals living in regions experiencing large tidal fluxes not only witness changes in intensity but also changes in light quality that may have substantial effects on photosynthesis. Particles in the water column such as phytoplankton and suspended sediments further attenuate and alter the spectrum of light. Highly turbid water may reduce benthic irradiance to critical light levels, compromising rates of photosynthesis for organisms like corals and marine plants[7,8]. Conversely, given that light intensity is a measure of the number of photons passing through a fixed area in a set period of time, the shape of waves and the presence of diffuse or reflective surfaces can amplify the intensity of light by trapping or focusing photons in a specific area. This phenomenon has been shown to occur frequently in shallow lagoonal waters, and has been argued to occur between the branches or even within the tissues of reef building corals[60].

#### 10.2.2.2 Sensitivity – light and ultraviolet radiation

The light intensity experienced by most photosynthetic organisms is neither constant in the short term (minutes to hours), nor constant in the long term (days to months). An imbalance between the amount of light energy capture and the ability to process that energy leads to the formation of damaging oxygen radicals. However, inadequate capture of light energy leads to scenarios where respiration (or metabolic activity) rates exceed photosynthetic rates impacting on growth and reproduction.

To maximise growth and limit damage, photosynthetic organisms therefore tend to optimise their ability to capture and process light energy to the prevailing environmental light regimes. The outcome is that some photosynthetic organisms are high light specialists, while others are low light specialists, with a few that are flexible enough to accommodate a large range of light intensities. The ability to accommodate a range of light intensities is genetically set by the ability to express proteins that allow for the restructuring of the antennae or the electron transport chain[148]. A photosynthetic organism that can handle two light extremes will appear bleached under the high light environment compared to the low light environment due to having expressed proteins that bind less chlorophyll. In contrast, a low light specialist will look bleached in the high light field due to the photo-oxidation of the antennae due to the activity of accumulated singlet oxygen on the histidine ligands that bind the pigment to the protein template. Bleaching in the latter case is more likely to result in mortality[2].

In corals, dinoflagellates sit within the symbiosome (vacuole) membrane of the coral host cell. These symbiont-containing host vacuoles may be stacked on top of each other within the coral gastroderm leading to a highly heterogeneous light field where deeper dinoflagellates are significantly shaded[61]. The host cell may contain flexible pigment-proteins that modulate not only light intensity but also spectral quality[52] (J Deckenback pers comm). The host may place dinoflagellates within tentacles that can be exposed or withdrawn based on specific spectral cues[122]. Alternatively, the host may alter its skeletal morphology to trap light effectively and reduce the effect of self-shading[143,8,60] or even maintain fewer symbiotic dinoflagellates to limit self-shading at the expense of dinoflagellate respiration. As these mechanisms have been uncovered, there has been an increasing awareness of the multiple mechanisms that may be in operation even within a single species with no two individuals resorting necessarily to the same set of solutions.

In addition to host variability, there is considerable variability among genetically distinct varieties of *Symbiodinium*. Cultured *Symbiodinium* have been classified as high, low light specialists or generalists according to their ability to restructure their antennae[92]. Genetically distinct *Symbiodinium* have been found to occupy light associated niches within a coral branch[166], yet there are examples of very tight coupling between symbiont and host genotypes[116]. More often than not corals transplanted from one light environment to another undergo changes to the concentration of chlorophyll per dinoflagellate cell, rather than in the number of dinoflagellate cells present[61,88,64]. However, this is not always the case with some host colour morphs experiencing no change in dinoflagellate chlorophyll or cell concentrations, but rather compensating changes in host pigmentation (S Dove unpublished data). In some instances, upon transplantation, coral hosts maintain a specific symbiont genotype despite the fact that conspecifics in the new light regime host a distinct symbiont genotype (E Sampayo pers comm). The flexibility associated with accommodating changing light regimes can therefore lie with a flexibility to express physiologically different *Symbiodinium* or with flexible symbiont or host gene expression.

Changes in light quality as opposed to quantity can have a significant effect not only on photosynthesis but also on a range of processes that are essential for maintaining healthy reproducing organisms. These include the setting of circadian clocks and the induction of defensive strategies. In higher plants, light quality plays an important role in balancing photosystem II and photosystem I (PSII/PSI) dynamics with the consequence that plant photosynthesis is most efficient when plants are illuminated with light of similar spectral quality to that in which they were grown[190,189]. Pigments such as red light sensitive phytochromes and blue light sensitive cryptochromes are involved in setting the circadian clocks. In addition to this role, phytochromes shift between active and inactive forms in response to different wavelengths of light, particularly red (which is absorbed by photosynthetic organisms) and a red irradiation. These wavelengths provide proximity meter for shade avoiding plants to grow and project into regions of un-attenuated light[173]. Photolyases that repair certain types of UVB damage to DNA are induced by blue or UVA light[141].

The role of different wavelengths in stimulating behaviour or genetic response in corals is less well characterised. Levy et al.[122] showed that some coral species retract their tentacles in response to both blue and red light, while others only respond to blue light, and others do not respond at all. Kinzie and Hunter[104] showed that in comparison to red and green light, blue light stimulated increased chlorophyll a densities in corals, arguing that the relative proportion of blue light increases with depth and hence signals reductions in overall light intensities that necessitate improving the light capturing ability of the antennae. While corals and their symbionts are able to synthesis cryptochromes and photolyases (R Reef pers comm), their functional roles are yet to be elucidated. Photosynthetic action spectra have been provided for some, principally non-symbiotic, dinoflagellates[158]. The specific action spectra of PSI, isolated from PSII has yet to be determined for *Symbiodinium* making it difficult to access whether changing spectral quality can result in an imbalance PSI/PSII dynamics.

Reductions in cloud cover and depletions in the ozone layer increase the UVR dose to which organisms are exposed. In clear tropical waters, UVR is principally attenuated by the presence of dissolved organic matter with UVB reduced to 1 percent of surface irradiance by a depth of approximately 11 metres[55]. In response, most organisms have developed mechanisms to either protect themselves from UV damage, or repair DNA damage as it occurs. Protective mechanisms for organisms that are sessile usually involve the production of mycosporine like amino acids (MAAs), compounds that have high extinction coefficients in the UV. These compounds are abundant in corals above 10 metres, and are believed to originate from host diet or be translocated from their endosymbiotic dinoflagellates[54,108]. DNA repair mechanisms either use specific enzymes (photolyase) that harness light energy to reverse DNA damage, or involve a group of genes (nuclear excision and repair genes) that cooperate in the removal and replacement of damaged DNA. The ability of corals and dinoflagellates to repair UV damaged DNA is yet to be explored. While the ability to synthesise MAAs was initially only linked to clade A *Symbiodinium*[17], this may be because only a few clade C *Symbiodinium* were analysed in this study, subsequent investigation has shown that some clade C *Symbiodinium* also appear to contain MAAs[63].

Given that much DNA damage occurs indirectly through the creation of reactive oxygen species due to the interaction of UVR with photosensitisers in an oxygen rich environment, antioxidants play a major role in limiting damage. Both the host and the dinoflagellate may contain photosensitising pigments. Chlorophyll is the most abundant photosensitiser in photosynthetic organisms. Significantly, another fluorescent photosensitiser (named appropriately *killer red* for its ability to kill bacteria is an all protein chromophore isolated from a hydrozoan and which is structurally similar to the range of proteinaceous GFP-like compounds) that have been identified within the pigmentation of corals[33]. Interestingly, pigments can also act as effective antioxidants as is best exemplified by carotenoids. As yet, the full range of antioxidants available to either host or symbiont is yet to be determined, it may even turn out that while some GFP-like compounds expressed by hosts are photosensitisers potentially mediating the appropriate defensive response to increases in photon flux density, others may act as antioxidants (M Lesser pers comm).

### 10.2.2.3 Impacts – light and ultraviolet radiation

Global weather patterns are changing. This is specifically true of southeast Queensland in Australia where drought conditions persist and are infrequently broken up by heavy rainfall. Correlated with these drought conditions is an observed increase in the number of cloud free days over the southern GBR (M Nunez, pers comm). Sustained insolation increases sea surface temperature and places additional stress on photosynthesis as existent pools of antioxidants and other defensive pools are used up. Infrequent and heavy rainfall is also undesirable for communities of corals as it leads to turbid freshwater flood plumes that can drastically attenuate light in the water column[7].

Additionally, the formation of low temperature cloud particles in the stratosphere provide the surfaces required by reactions, which catalysed by light, that lead to the destruction of ozone. This phenomenon is observed every spring over Antarctica as clouds formed in the winter are exposed to solar radiation. The stratosphere is believed to be cooling as a result of climate change because green house gases trap heat in the troposphere and prevent its escape to the stratosphere. There is therefore a growing concern that climate change may result in an exponential increase in global levels of UVB.

### 10.2.2.4 Adaptive capacity – light and ultraviolet radiation

It is difficult to access how corals and their endosymbionts will respond to exponential increases in UVR, given that we do not know whether they have DNA repair mechanisms in addition to MAAs and an antioxidant defence mechanism. Given that increased and sustained light stress, at least in the Southern portion of the GBR, appears to co-occur with increasing temperature, it is necessary to ask how stable MAAs and this antioxidant defence system are at elevated temperatures. The answer is perhaps not so promising. Lesser et al.[121] found an inverse correlation between temperature and host tissue MAA concentrations. Equally, if the flexibility to handle high light is dependent on either the symbionts or host ability to acclimatize to the changing light field then it must be hoped that elevated temperature does not interfere with this ability. Experimentally, it has been shown that increasing temperature in a low light field decreases the concentration of the xanthophyll pool, potentially limiting the ability of *Symbiodinium* to divert excess excitation energy to heat[53]. Similarly, it has been demonstrated that while some forms of host pigmentation appear to correlate with increased photosynthetic performance at lower temperature, corals that are able to express these protein-pigments in high concentrations die as threshold temperatures are attained[50]. Threshold temperatures have been correlated with a reduction in mRNA concentrations for genes encoding these proteins[171].

Conversely, however it has been shown that corals that have been exposed in the long term to high light fields cope better (lose fewer symbionts) with increases in temperature[29]. Closer analysis showed that the host rather than the symbiont antioxidant system was most active on the high-light surface of the coral, although dinoflagellates on the sunlit side of the coral had a significantly larger xanthophyll pool[30]. An examination of the literature shows that few *Symbiodinium* cultures have been trialled for both heat and light tolerance. Of the few, the exclusively high-light adapted A2 *Symbiodinium* from *Zoanthus* sp. is able to tolerate relatively high temperature. The high- and low-light flexible A1 *Symbiodinium* from *Cassiopeia* sp. is intolerant of high temperatures[92,93]. Perhaps the message is that if a symbiont is already expressing defence mechanisms that enable it to deal with increased excitation pressure at PSII, then it can survive a limited additional amount of excitation pressure generated by temperature stress. However if the appropriate defence mechanisms have not previously been induced, then temperature stress above a given threshold will not enable them; despite having potentially enabled key enzymes in the water-water cycle[121].

In this context, the massive amplification of light within the tissues of corals that is predicted to occur during a severe bleaching event, due to the trapping of unimpeded photons by the diffuse and reflective skeletal surface of a scleractinian coral may account for coral mortality[60]. The scenario has been referred to as *photon hell*, which may be appropriate given the lethal doses of UVR or photosynthetically active radiation that are likely to be generated for host and remaining symbiont cells alike.

### *10.2.2.5 Vulnerability and thresholds – light and ultraviolet radiation*

Corals show high sensitivity to light and UVR levels. This sensitivity increases under thermal stress due to blockages of electron flow through photosynthesis, essentially pushing thresholds for light exposure downwards. Increases in light and UV are occurring in tropical and subtropical Australia. These changes, however, are small. Under conditions in which climate change is not occurring, corals are only vulnerable to changes in light and UV to a small extent. This changes dramatically, however, as waters warm. Dramatic changes in the vulnerability of corals and their dinoflagellate symbionts occur as climate change occurs. The demonstration that thermally stressed corals bleach less and survive better if they are shaded during thermal stress reinforces this conclusion, and also suggests that some small scale technologies (eg shading) may successfully reduce the impact of thermal stress on local coral assemblages.

## 10.2.3 Changes in ocean chemistry

### *10.2.3.1 Exposure – ocean acidification*

The present-day chemistry of the oceans is fundamental to the ability of reef-building corals to calcify and hence form the massive calcium carbonate framework of tropical coral reefs. The oceans have absorbed at least one-third of the excess $CO_2$ produced by human activities that has entered the atmosphere[159,107]. On entering the ocean, $CO_2$ reacts with water to form carbonic acid, which dissociates to form bicarbonate ions and protons. These protons react with carbonate to form bicarbonate, moving the ionic equilibrium from carbonate to bicarbonate as more $CO_2$ enters the ocean[159]. As the oceans take up $CO_2$, ocean pH and the saturation states of carbonate minerals (calcite, aragonite and high-magnesium calcite) decrease. These minerals are fundamental to the formation of skeletal structures in many marine calcifying organisms such as corals. The reduced carbonate ion concentration significantly reduces the ability of reef-building corals to form their skeletons and hence the reef structures that house hundreds of thousands of marine species.

### *10.2.3.2 Sensitivity – ocean acidification*

The decrease in carbonate ions represents a major problem for calcifying organisms such as corals given that the rate of calcification varies linearly with the carbonate ion concentration[118,159]. Various lines of evidence indicate that coral calcification rates will decrease and carbonate dissolution rates

increase as the calcium carbonate saturation state decreases. Several controlled experiments of calcification rates under elevated $CO_2$ levels confirm that calcification rates decrease with increasing $CO_2$ levels. These measurements suggest that calcification rates may decrease by up to 60 percent with a doubling of atmospheric $CO_2$ concentrations by end of 21st century. This may put reef structures into net erosion with long-term implications for coastal protection[85].

### 10.2.3.3 Impacts – ocean acidification

Cores drilled from long-lived massive corals such as massive *Porites* spp provide insight into how calcification has changed over the past centuries. Some studies[127,25], reported evidence of a slight increase in calcification over the decades prior to 1979 with calcification being highly correlated with average sea temperature (0.3 grams per $cm^2$ per year or 3.5% increase for each degree C of increase). Lough and Barnes[127] have proposed that the increase in calcification was probably due to the 0.25°C observed increase in sea temperature on the GBR during the same period and that, initially, some corals may increase their calcification rates as the oceans warm. There is, as yet, no observational evidence of decreases in coral calcification rates on reefs with the 0.1 drop in oceanic pH, though significant decreases have been observed in controlled laboratory experiments.

### 10.2.3.4 Adaptive capacity – ocean acidification

Another group of authors[133] have used the observation of increased calcification over the past 100 years to conclude that the ocean acidification will be counteracted by the putative increase in calcification due to future warmer conditions. This assumption is invalid given that corals start to bleach at just 1°C above today's sea temperatures, and that the physiological literature also unambiguously shows that calcification increases up to the summer sea temperature maxima but then decreases rapidly thereafter[106]. Contrary to the predictions of the McNeil et al.[133] model, combinations of high sea temperatures and high $CO_2$ concentrations of future climate scenarios predict dramatic decreases in calcification rates. There would need to be an ever-increasing calcification rate (and a lack of negative influences from thermal stress) to enable the McNeil model to have any credibility. This and other problems with the methods and conclusions of McNeil et al.[133] are outlined and fully discussed in Kleypas et al.[106]. It seems that the ability of marine calcifying organisms such as corals to adapt to the unprecedented and rapid rates of changes in ocean chemistry, combined with additional stresses resulting from climate change (eg coral bleaching and more destructive tropical cyclones) will be limited.

### 10.2.3.5 Vulnerability and thresholds – ocean acidification

Doubling atmospheric $CO_2$ above the ocean will cause the carbonate concentration to decrease to approximately 200 micromol per kg, with temperature having a small influence. A carbonate concentration of 200 micromol per kg is critical in that the calcification of corals and many other organisms declines effectively to zero at carbonate concentrations around this value. This impact is made even more significant because coral reefs are a balance between calcification and erosion and hence calcification needs to be well above zero to avoid a net erosion of coral reefs. There is overwhelming evidence that corals and the reefs they build will not be able to maintain themselves or grow if $CO_2$ concentrations rise above 500 parts per million[67,105,78,85,107]. This level of $CO_2$ is at the lower end of the range of greenhouse scenarios for the end of this century.

## 10.2.4 Sea level rise

### *10.2.4.1 Exposure – sea level*

Coral reefs of the GBR have adjusted to sea levels that have prevailed for the last 6000 years (since current level reached at end of last Ice Age). Current sea levels, therefore, are one of the controlling factors in terms of coral distribution on the GBR in terms of water depth. Global sea level is rising due to the enhanced Greenhouse effect due to both thermal expansion (of the warmer ocean waters) and contributions from the melting of continental ice sheets and glaciers. Changes to sea level have been of the order of about 20 to 25 cm over the past century[155,36] and sea level is currently rising at 1 to 2 mm per year, an order of magnitude larger than the average rate over the previous several millennia[37]. Current projections[94] suggest a 0.1 to 0.9 metre rise of sea level by 2100. There is however, mounting concern that this rise in sea level may be higher as the Greenland Ice Sheet has been observed to be melting faster than expected. Loss of both the Greenland Ice Sheet and West Antarctic Ice Sheet would result in global sea levels that are more than 10 metres higher than present.

### *10.2.4.2 Sensitivity – sea level*

Previous reviews have all concluded that these changes in sea level are relatively slow when compared to the rate at which corals are able to grow (up to 20 cm per year for branching corals[47]), and hence do not represent a major challenge for healthy coral populations. However, these maximum coral growth rates are rates of linear extension for individual coral branches, not the reef matrix itself. In addition, the emphasis is on healthy corals, which in turn may depend on the effect of rising sea temperature and ocean acidification, and on other stressors such as reduced water quality (eg turbidity and sedimentation).

### *10.2.4.3 Impacts – sea level*

Due to the slowing effect of other factors on growth, there is the potential that coral populations might be left behind by rapid sea level rise. It is also important to keep in mind that these conclusions are dependent on having a slow rise in sea level. They would be invalidated in the longer term if, for example, the Greenland Ice sheet were to melt rapidly[152]. If this were so, then sea level rise would accelerate well above coral growth and would stabilise at 6 to 10 metres above current sea level. In this case, sea level rise would represent an extreme challenge for most marine habitats including coral reefs.

### *10.2.4.4 Adaptive capacity – sea level*

A steady, relatively modest (eg 0.1 to 0.9 metres by 2100[94]) rise in sea level is unlikely to be a major problem for corals of the GBR as reef development has been constrained by current sea levels reached several thousand years ago. Corals with high growth rates may be able to keep up with projected sea-level rises. The potential for adapting to rising sea level depends, however, on healthy coral populations which is unlikely to be the case as continued ocean warming (increasing bleaching events) and ocean acidification (reducing calcification rates) compromise the viability of corals on the GBR.

### *10.2.4.5 Vulnerability and thresholds – sea level*

Corals of the GBR are probably less vulnerable to gradual and modest sea-level rise than to other climate change stressors. There is, however, mounting concern that the global rise in sea level is accelerating[36] and that the potential for catastrophic rises (of greater than 10 metres) may be triggered by loss of the Greenland Ice Sheet and, possibly the Western Antarctic Ice Sheet. Under such circumstances, extensive areas of coral communities on the GBR would be lost or compromised, as rapid changes in sea level would overwhelm the growth rates of corals pushing their communities into deeper, low-lit areas of the ocean. A massive contraction of coral distributions would almost certainly occur, in particular in coastal, turbid areas where photic zones are already compressed, until the climate stabilised once more.

## 10.2.5 Tropical storms, rainfall and river flood plumes

### *10.2.5.1 Exposure – storms and floods*

The number of severe cyclones (category 4 and 5 on the Saffir-Simpson scale) has nearly doubled over the past three decades in all ocean basins[193,59]. Using an index based on power dissipation during the life of each cyclone, Emanuel[59] showed that cyclone destructiveness has increased dramatically since 1970, correlated with the increase in tropical sea surface temperatures. The record number and intensity of storms in the Gulf of Mexico during 2005 (a record 28 storms of which 15 were classified as hurricanes with winds greater than 100 km per hour[b]) underscored the conclusions of both studies. If this trend in destructive cyclone activity continues to rise and interact with other climate change stressors, coral reefs will enter an era of disturbance of unprecedented dimensions.

### *10.2.5.2 Sensitivity – storms and floods*

Storm impacts are part of the natural disturbance regime on coral reefs, and in some areas may help maintain high species diversity by preventing monopolisation by competitively dominant species[42,44]. However, whereas intermediate disturbance regimes can favour ecosystem health, increased frequency of severe cyclones, such as those predicted for this century, may lead to physical damage and associated stressors beyond what reefs have previously experienced. One basic premise of the intermediate disturbance hypothesis[42] is that the disturbance frequency and/or severity are low enough to allow succession of the benthic community between events. Importantly, if the frequency or intensity of destructive storms increases beyond the reef's capacity for recovery between events, reef resilience will decline and may shift reefs into alternative, less desirable states[47,91].

Benthic communities reset to bare substrate and algae following severely destructive events will recover mainly through the slow process of colonisation by sexual recruits[43]. Milder cyclone impacts, on the other hand, often allow survival of some adult colonies that can recolonise bare patches by regrowth[44]. Communities of corals in coastal areas may be particularly sensitive to intensified cyclone regimes as associated secondary impacts such as terrestrial runoff and sediment resuspension will also escalate under intensified cyclone regimes (section 10.2.5.3). Interestingly, however, the shading and cooling effects of the often dense cloud cover[142] and enhanced surface convection associated

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[b] http://www.nhc.noaa.gov/2005atlan.shtml

with storms in regions beyond their primary impact area may alleviate risks of coral bleaching. For example, during late 2005, coral reefs in the southeastern Caribbean experienced the warmest sea surface temperatures and associated mass bleaching in history[c]. The passing of Hurricanes Katrina and Rita in the northern Caribbean in August to September, prior to substantial heating of the southern Caribbean, led to significantly reduced sea surface temperatures, solar irradiance, and thereby lowered bleaching risks (M Eakin pers comm). It is important to note, however, that such lowered bleaching risks on reefs in marginal impact areas are likely to be counteracted by the increased mortality risk from secondary stressors (eg runoff and sedimentation) in coastal areas subjected to major flooding events.

### 10.2.5.3 Impacts – storms and floods

The impacts of tropical storms extend well beyond the direct physical impact of the wind waves they generate. Secondary impacts following storms like Hurricane Andrew were more important than the physical impacts during the storm through changes in coastal runoff and reduced water quality in nearshore areas[156]. In coastal areas, tropical storms often lead to heavy rainfall and associated runoff on the scale of 100s of kilometres[62], whereas the destructive wind forces occur on a scale of 10s of kilometres. Major flooding events are runoff of freshwater and dissolved nutrients from coastal catchments is perhaps the biggest threat to corals in nearshore waters[45]. Freshwater plumes[34] and increased nutrient loading[45] may inundate reefs within 50 km of major river mouths. Although terrestrial discharges of suspended solids are deposited within a few kilometres of river mouths[65], resuspension of sediment due to wind waves[114] may reduce benthic light regimes dramatically[8], compromising coral energy budgets[7]. As these secondary impacts may persist for weeks following a cyclone[45], and may extend over a larger area than the physical impact area, they may cause far more damage to reefs than the structural impact *per se*. Given the recent tropical cyclone activity around Australia's coral reef coastlines, changes in storm intensity on Australian reefs are likely to be similar to those seen for other coral reef regions.

### 10.2.5.4 Adaptive capacity – storms and floods

Given that coral reefs have evolved under a stochastic, natural regime of storms, they undoubtedly have some capacity for adapting to locally intensified storm regimes. The more critical question is perhaps whether reefs can tolerate an intensified storm regime as well as impacts from multiple other stressors that are also predicted to intensify in the future. Perhaps most importantly, ocean acidification through increasing $CO_2$ levels (section 10.2.3) will severely reduce the capacity of corals to build skeletons[105] and potentially the ability of crustose coralline algae to consolidate the reef matrix (Diaz-Pulido et al chapter 7). Since increased erosion of calcium carbonate will increase the susceptibility of reefs to storm damage, the adaptive capacity of coral reefs to physical disturbances is likely to be rapidly exceeded. Future communities of corals will most likely lack high-diversity assemblages of branching *Acropora*, but may enter a phase of largely massive and/or semi-encrusting morphologies that have higher resistance to wave impacts.

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[c] http://coralreefwatch.noaa.gov/caribbean2005

### *10.2.5.5 Vulnerability and thresholds – storms and floods*

The vulnerability of coral reefs to increased storm intensity and flooding is highly interactive with the other side of the equilibrium within which coral communities sit. Major disturbances like category 5 storms can have a major impact on sections of coral reef yet are (currently) fairly infrequent events. Recovery from these natural events occurs over several decades and in past climate regimes has not led to any persistent decrease in coral community abundance. This equilibrium may shift as the frequency of catastrophic storms increase and recovery processes become increasingly compromised through ocean warming and acidification. This suggests that coral communities will become increasingly vulnerable as storm activity increases and recovery processes decline. Specific thresholds have not been identified. However, several modelling studies[96] have revealed that coral populations are highly sensitive to small changes in mortality or recruitment. This suggests that thresholds should be relatively easy to identify.

## 10.2.6 Changes in ocean circulation

### *10.2.6.1 Exposure – ocean circulation*

One of the ways the planet copes with differential heating patterns is to balance the energy budget by transporting heat from the tropics to the poles, which is achieved by both large-scale air and ocean currents. Ocean currents are driven by wind as well as fluxes of heat and freshwater, the latter referred to as thermohaline circulation. In our present climate, the sinking of cold water near Antarctica and in the northern Atlantic Ocean are drivers for a major conveyor system known as the Atlantic meridional overturning circulation[31]. Cold, dense water in these regions sinks to the bottom of the ocean from where dense flows spread toward the equator at great depth eventually rising to the surface and being returned to the poles. The Gulf Stream is the major surface current that closes the northern arm of the meridional overturning circulation and runs from the Caribbean, along the east coast of the USA to the Greenland-Norwegian Sea. It is this current that has the greatest sensitivity to climate change. At the edge of the GBR, the East Australian Current plays a major role in determining many of the environmental conditions discussed above that can influence coral condition. In addition to influencing basic water quality, the behaviour of these currents affect whether communities of corals are connected or not, and aspects of coastal weather (such as storms and doldrums) which in turn drive parameters that affect corals. Steinberg (chapter 3) discusses these large-scale variations.

### *10.2.6.2 Sensitivity – ocean circulation*

Since the drivers for the meridional overturning circulation are primarily the Artic and Antarctic ice sheets and to a lesser extent tropical heating, any change to the volume of ice at high latitudes, their melting rate, or heat input at low latitudes could affect the speed of this current. Melting of the Greenland and Antarctic ice sheets is happening at much faster rates than previously thought[152] and the resultant freshwater influx has the potential to slow down or even halt the North Atlantic meridional overturning circulation. The warm surface water of this conveyor forms the Gulf Stream, which normally provides northern Europe its relatively mild climate. A slowing down of the Gulf Stream is likely to abruptly and profoundly influence the climate of the northern USA and Europe with likely flow-on effects to the climate of the rest of the world. To a large extent, our understanding of the impact of climate change on ocean circulation is still rapidly evolving. It is clear, however, that many parts of the ecosystem are highly sensitive to changes in global temperature, and that coral reefs are highly sensitive to these changes.

### *10.2.6.3 Impacts – ocean circulation*

Paleo-proxy records of the northern hemisphere show that a slowing down or halting of the North Atlantic meridional overturning circulation has occurred on a number of occasions in the past. The last major abrupt climate change occurred some 8200 years ago when two glacial lakes melted and drained into Hudson Bay, Canada[38,119]. This event is recorded in the $\delta^{18}O$ signature of Greenland ice cores and is estimated to have caused a 3 to 6°C decrease in northern European temperatures within a few years[4,161]. Bryden et al.[31] provide observational evidence that the oceanic density fields in the North Atlantic have changed considerably resulting in a weakening of the circulation of more than 30 percent between 1957 and 2004. A repeat breakdown of the circulation would have devastating effects on the socio-economic condition of countries bordering the eastern North Atlantic. The flow on effects to coral reef regions under such a scenario are uncertain, but could include enhanced warming and tropical storm activity in the Caribbean and global sea level rise[94], the consequences of which are discussed in sections 10.2.1.4, 10.2.4.3 and 10.2.5.3.

Although projecting the precise details of how ocean circulation will change is difficult, it is quite clear from current evidence that it is changing and that coral communities are highly sensitive to change. Currents determine aspects of the environment such as temperature and to an extent local weather. To see the effects of relatively minor changes in ocean currents on coral communities one has only to examine the large scale changes that have resulted during El Niño-Southern Oscillation (ENSO) disturbances to the Indo-Pacific in the 1982–1983[73] or 1997–1998 global ocean-atmosphere events[82]. The latter event involved changes (as was the 1982–1983 event) to ocean circulation and led to the loss of 16 percent of reef-building corals globally.

### *10.2.6.4 Adaptive capacity – ocean circulation*

Forcing of ocean currents are subject to physical laws. As such there is little scope for 'adaptation' in the same sense as biological and human systems can adapt to changes. Ocean currents change in response to regional changes in heat fluxes, freshwater input, wind forcing and sea ice volume. These forcing factors interact in complex ways and themselves are a response to local and regional climate variation. For this reason anticipating the timing and dynamics of ocean currents is difficult to predict.

### *10.2.6.5 Vulnerability and thresholds – ocean circulation*

Under present climate change models, the likelihood of a shutdown or slowdown in the North Atlantic meridional overturning circulation of sufficient magnitude to cause a cooling in the Europe is considered small (despite the large-scale changes it would bring). Meehl et al.[136] modelled the latent response of our climate system using two independent climate models and showed that even under a high-end A2 climate scenario, there was no cooling over northern Europe despite significant slowing of the meridional overturning circulation. This is principally because increases in greenhouse gas emissions and resultant warming overwhelmed any tendency to high-latitude cooling. The IPCC[94] notes that it is too early to say with confidence whether an irreversible collapse in the Atlantic

meridional overturning circulation is likely or not and at what threshold it might take place. However, none of the coupled models predict a complete shutdown of the current under any of the climate scenarios by 2100.

### 10.2.7 Linkages with other components

#### *10.2.7.1 Constraints to adaptation*

Evidence for past adaptation of corals to distinct thermal regimes comes from the observation that populations from warmer locations can withstand higher temperatures compared to conspecific or congeneric populations that live in cooler water, and that those differences are maintained after laboratory acclimation[41,82,185,22,171,173]. These results suggest that variation in bleaching resistance of corals has a significant genetic component, which is a prerequisite for selection to lead to adaptive change. In other words, if all of the observed variation in bleaching resistance reflected phenotypic plasticity, corals would be unable to respond to selection for increased temperature resistance and hence would not adapt.

To predict the rate at which corals and their algal endosymbionts can potentially adapt given the most likely warming scenarios, it is useful to quantify the extent to which the observed variance in bleaching resistance is genetically determined using quantitative genetic approaches. This information is currently unavailable. A second important factor in estimating potential rates of adaptation of corals is the generation time, that is, the time period from birth to average age of reproduction. The longer the generation time, the slower the process of adaptation. Generation times in corals depend on their growth rates, as reproductive maturity is related to size[12]. The age at first reproduction is probably on the order of three to eight years, but because corals are iteroparous, the generation time should be a weighted average of the age of a maternal colony at which each of her offspring was produced[154]. Generation times for long-lived coral species that grow to large sizes are therefore expected to be significantly longer than three to eight years, as most offspring will be produced when the maternal colonies are large (ie at an older age) and after adult polyp fecundity has been reached[12].

*Symbiodinium* populations, on the other hand, are asexual in *hospite*, but population genetic studies show that sexual reproduction does occur although it may be infrequent[13,14,115,168]. *Symbiodinium* occurs at extremely large populations sizes (probably on the order of several billion cells per coral colony). Therefore, even in the absence of frequent sexual reproduction, infrequent somatic mutations may become relevant in such huge populations. Aided by clonal reproduction, selection may lead to the rapid dominance of cells that have undergone a mutation, which enhances thermal tolerance. This is very hypothetical, and experimental work should be directed to explore the likelihood that such evolutionary processes play a role in the evolution of *Symbiodinium*. Furthermore, it is unknown whether *Symbiodinium* with enhanced thermal tolerance will also increase the thermal tolerance of the holobiont.

In any of these discussions about the adaptation of populations of corals to climate change, it is important to note that climate change does not involve a step change but rather, is (and will continue to be) characterised by continuous change. This has important implications for the expectation of how populations of corals and other coral reef organisms may change. For example, if we were to stabilise global temperatures at 2°C above present day conditions, coral populations would see an initial decrease in population size as unfit genotypes are eliminated followed by the proliferation of fit genotypes at the new temperature. We might also expect the migration of thermally tolerant northern genotypes to migrate to southern locations on the reef over time (probably over decades), assuming that levels of gene flow are sufficient to accomplish this, and to flourish at these southern locations as conditions stabilised. The key part of this preceding statement is the stabilisation of climate, which is highly dependent on the rate of greenhouse gas emissions achieved over the next few decades. Stabilisation of climate becomes increasingly unlikely with anything less than aggressive reductions of greenhouse gas emissions (greater than 80% by 2050). Given that stabilisation is unlikely, notions of rapid adaptation changing the thermal thresholds of corals and their symbionts in whole communities are also unlikely. In the unlikely event that we could stop all greenhouse gas emissions today, we are still committed to significant climate change and disruption to habitats like coral reefs[136,195] before stabilisation is reached.

### *10.2.7.2 Interactions between stressors*

There are a large number of interactions between stressors, producing either muted or enhanced outcomes for corals and *Symbiodinium* as two or more factors coincide. These interactions have not been exhaustively pursued and should be the subject of future research work. Interactions between thermal stress and light have been explored at both physiological[101] and ecological[142] levels and via modelling[82]. As discussed above, the flow of water around corals also has an important effect on thermal and photic stress[144,145] and effects on the photosynthetic performance of zooxanthellae in hospite have also been documented[184]. Anthony et al.[9] explored the interaction between water quality, light and temperature, on coral bleaching and mortality and found that the complex interactions between these variables are largely explained by their effects on coral energetics. These interactions ultimately define environmental limits to growth[7] and are ultimately related to common variables within the energy budgets of corals that are attempting to undergo photosynthesis in the challenging conditions associated with life in coastal water.

Despite the fact that much is known about the interaction of some variables, we have only a hint of how factors such as thermal stress and acidification will interact under future oceanic conditions. As discussed above, the poorly constructed conclusions of McNeil et al.[133] stemmed from inaccurate assumptions about how coral calcification might fair in a warmer more acidic ocean. This highlights the importance with which we must address the questions of how different drivers will interact as the world changes. For example, the process of recovery of coral reefs following bleaching events is surprisingly poorly described despite the importance given to the concept of resilience. How fishing pressure affects reef recovery, or how poor water quality affects mortality following thermal stress need to be determined if we are to understand and better manage the impacts that appear almost certain as the global ocean warms and acidifies.

### *10.2.7.3 Coral disease*

Recognition that coral disease can be a major force in structuring coral communities has emerged only recently and has been based primarily on studies of Caribbean reefs in the past two decades[11,157]. The first record of a coral disease was in the early 1970s[10], but since then, more than 30 coral diseases have been described, the majority from the Caribbean (reviewed in Weil[194]). Disease is commonly defined as a deviance from the normal physiological functioning of an organism, but the distinction

between health and disease is not always clear-cut. The distinction is typically based on the extent of the dysfunction; mild dysfunctions of behaviour, growth and reproduction generally fall within the realm of relative health, whereas severe dysfunctions and mortality are classified as disease. Coral diseases may be either infectious or non-infectious (eg environmentally induced). Infectious diseases of corals are associated with a variety of pathogens, including bacteria, cyanobacteria, ciliate protists, and fungi, although causative agents (as verified using Koch's postulates) have been identified for only a few coral diseases (reviewed in Weil[194]). Surveys of coral disease reveal generally low (less than 5%) disease prevalence on reefs in the GBR[198]. Overall, seven disease types have been recorded: black band disease (BBD), skeletal eroding band (SEB), white syndrome (WS), brown band disease (BrBD), coral tumors, atramentous necrosis, and cyanobacteria syndromes (other than BBD), although current understanding of the majority of these is limited to field descriptions of lesions. All seven of these coral diseases are widespread throughout the GBR. For example, BBD occurs on more than 70 percent of reefs surveyed (n = 19) throughout the northern, central and southern sectors, although its prevalence is typically low (affecting about 0.1% of scleractinian corals)[153]. Black band disease has been recorded to infect at least 32 coral species in 10 families on the GBR, with branching pocilloporid and acroporid corals being important hosts[198]. Abundance of WS increased 20-fold in the 2001 and 2002 period, around the time of the most severe bleaching event so far recorded on the GBR, and increased further in 2002 and 2003[198] but has since declined to low levels in all regions (B Willis and C Page unpublished data). Detection of some of the more common and infectious Caribbean diseases (BBD and potentially some of the white diseases), in combination with discovery of diseases unique to the region (brown band disease[198]), suggest that coral diseases are common on Indo-Pacific reefs and may have a greater role in structuring Indo-Pacific coral communities than previously thought. Diseases are ubiquitous in all plant and animal populations, thus such contributions to the dynamics of coral populations are not unexpected. Increases in white syndrome abundance[198] and atramentous necrosis in the summer of 2001–2002[102] are the only disease outbreaks so far documented on the GBR. At present, diseases have had a comparatively low impact on GBR coral populations in comparison to those in the Caribbean. However, the impacts of coral disease in other reef areas highlight the potential for increased risk in the future, especially in a warming climate.

Increasing reports of diseases in many marine organisms globally in the past few decades are postulated to be linked to ocean warming[80,113,191,170]. Increasing sea water temperatures have the potential to increase not only host susceptibility to disease, but also virulence of the pathogens themselves[80,163]. It is difficult to separate the effects of ocean warming from concurrent increases in stressors such as nutrients, toxic chemicals and other pollutants, based solely on reports of disease[113]. However, a number of additional lines of evidence support a link between elevated temperatures and disease. For example, the role of high temperatures in summer outbreaks of bacterially induced bleaching in Mediterranean populations of the coral, *Oculina patagonica*, appears to be well established[180,95]. These outbreaks have been linked to increased expression of virulence genes by the bacterium, *Vibrio shiloi*, at higher temperatures (reviewed in Rosenberg and Ben-Haim[180]). Seasonal patterns in coral disease prevalence on the GBR[198] and spatial patterns in black band disease abundance in the Caribbean[111] support a link between elevated temperatures and the prevalence of a number of coral diseases (eg white syndrome), black band disease, skeletal eroding band and brown band disease on the GBR[198]. Recent analyses of the relationship between annual patterns in the abundance of white syndrome on the GBR and warm thermal anomalies also corroborate a link between elevated seawater temperatures and coral disease[170]. Speculation that warmer winter temperatures will favour pathogen populations and therefore not provide a winter reprieve from pathogen load associated with current mean winter minima[81] represents another potential way in which climate change may affect disease dynamics in GBR coral populations.

It is noteworthy that, in addition to temperature and environmental stressors, biological factors may also affect disease incidence, thus predicting the vulnerability of coral populations to disease as a consequence of climate change is complex. Host density is known to affect pathogen transmission[5] therefore reduced cover of dominant coral species may lower the spread of disease once low host density thresholds are reached. It is also possible that pathogens, which are currently positively affected by summer temperatures, will be negatively affected at higher sea water temperatures associated with climate change. Furthermore, there may be reduced coral disease under climate change scenarios as elevated sea water temperatures negatively affected some pathogens[112]. Evidence that an acroporid tissue loss syndrome decreases in abundance during the summer months at Heron Island[162,3] supports this possibility. These studies have documented programmed cell death (apoptosis) as the mechanism underlying tissue loss, although the trigger (eg environmental stress or microbial pathogens) for cell death is unknown. The greater disease abundance in winter may relate to dwindling energy resources (perhaps due to thermal stress in the preceding summer) prior to entering the colder, darker months. In summary, the impact of ocean warming will depend on relative thermal optima of coral hosts and pathogens. However, the potential for rapid spread of pathogens throughout marine populations, as demonstrated by the rapid spread of herpes virus throughout Australian pilchard populations and of morbillivirus throughout seal and dolphin populations[130], highlights the need for greater understanding of mechanisms of coral pathogen transmission and virulence, as well as mechanisms of disease resistance of corals, to better evaluate the vulnerability of corals to disease as a consequence of climate change.

### 10.2.7.4 Threats to resilience

This chapter is devoted to the impacts of climate change on reef-building corals. It is important to note, however, that impacts on corals are likely to reverberate throughout the GBR ecosystem. Corals are responsible for the physical and ecological foundations that underpin reefs, making the fate of coral communities a critical determinant of ecosystem resilience. The many chapters in this book provide important insights into how impacts to coral communities from climate change will affect particular species or habitats. Emerging as important to understanding how impacts on corals might affect resilience more generally, is an awareness of the dependency between corals and other habitat components.

Corals support tens if not hundreds of thousands of other organisms. Many of these are totally dependent on corals for food, shelter and reproduction. Many others rely only partly on corals, while nearly every organism has some sort of indirect dependency on the goods and services provided by corals. Where direct and strong dependencies occur, changes in coral cover or composition can have obvious and immediate impacts on other species. Coral obligates like the orange-spotted filefish (*Oxymonacanthus longirostris*), for example, rapidly disappeared from Okinawan reefs after the 1998 bleaching event[109]. In contrast, less direct or facultative relationships can result in complicated, delayed or minor responses to changes in coral communities. In the Seychelles, for example, Spalding and Jarvis[174] found that the overall structure of fish communities had changed very little despite massive decreases (3 to 20 fold) in living coral cover after the 1997–1998 bleaching event. This effect

is amplified further up the trophic pyramid, as exemplified by the difficulty in detecting impacts on reef-based fisheries after major coral mortality events caused by bleaching[35]. Competitive interactions involving corals are also important to the composition and dynamics of coral reefs. The ability of corals to dominate available hard substrate to the exclusion of algae, for example, is fundamental to the long-term resilience of the ecosystem[131].

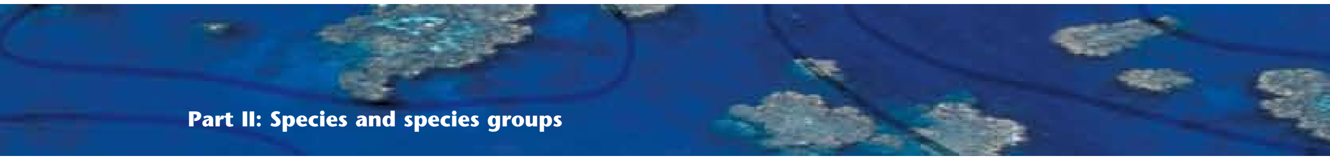
These illustrations highlight the complex web of relationships that centres on corals. Changes in the abundance or composition of coral communities will necessarily have impacts on other parts of the ecosystem, with the potential to severely undermine resilience. This emphasises the importance of measures that take into account the complex responses that are likely from inter-dependent ecosystems such as the GBR, rather than a focus on any one species, group or habitat. In the context of climate change, more than any other issue, understanding the connections between different parts of the ecosystem, and the role of species or groups in ecosystem resilience is critically important when formulating management responses. In particular, taking a resilience-based approach to the management of tropical marine ecosystems (McCook et al. chapter 4, Marshall and Johnson chapter 24) is critical to address the issue of climate change, where impacts are certain to occur, but their scale, intensity and frequency is largely unknown.

## 10.3 Summary and recommendations

### 10.3.1 Major vulnerabilities to climate change

The vulnerability of coral and the reefs they build to climate change was bought into sharp focus after 1998, when an estimated 16 percent of the world's coral communities died. Analysing the literature since that time reveals that rapidly rising sea temperatures and increasing levels of acidity in the ocean remain the major threat to coral reefs. Successive studies of the potential impacts of thermal stress on coral reefs[82,48,49] have supported the notion that coral dominated reefs are likely to largely disappear with a 2°C rise in sea temperature over the next 100 years. This, coupled with the additional vulnerability of coral reefs to high levels of acidification once the atmosphere reaches 500 parts per million[105,78,107], suggests that coral dominated reefs will be rare or non-existent in the near future. In this regard, we conclude that communities of Australian corals are extremely vulnerable to the effects of ocean warming and ocean acidification. While new assemblages will certainly form in the absence of coral-dominated reefs, the diversity and structure of these communities as well as the types of fishing and tourist industries they might support are completely unknown.

Changes to other factors such as storm intensity, water quality and light intensity will have a lower, yet significant, impact on coral reefs. Although coral reefs are less vulnerable to these particular factors, and hence they are likely to interact with climate change and ocean acidification in some important ways. Increased storm activity, for example, may reduce the effects of climate change locally by mixing the water column and cooling the overlying waters. Stronger storms, however, will accelerate the breakage of increasingly fragile coral skeletons caused by ocean acidification and will cause larger coral mortality events in coastal areas due to more intense flooding. Other factors such as increasing sunlight days as the Australian coastal areas undergo drying will exacerbate the effects of warming. Although a full understanding of the many interactions with secondary variables has not been achieved, their role in the vulnerability of coral reefs is likely to grow.



### 10.3.2 Vulnerability and thresholds (extinction risk and irreversibility)

As outlined above, 500 parts per million is the highest $CO_2$ concentration under which any semblances to the communities of corals we have today can survive. It is also the only scenario in which the climate will eventually stabilise. Above this point (500 parts per million), coral reefs will also change irreversibly and be lost for many thousands of years. To contemplate any higher $CO_2$ is untenable given the huge likelihood of such catastrophic events as runaway greenhouse effects and the flooding of the planet as the Greenland and Western Antarctic Ice Sheets melt. Even though 500 parts per million is seen as an ambitious greenhouse target, effects on ocean temperature and acidity will mean that coral calcification will decrease to 40 percent of today's value and major (1998 level) bleaching events will occur every 2 to 4 years[82,48,49]. Under these conditions, Australian reefs will have the following characteristics:

- Major increase in the frequency and intensity of coral bleaching, mortality events and recruitment failure with increased incidences and outbreaks of coral disease.
- Coral dominated reefs will contract to less that 20 percent of today's distribution and corals will be rare on most coral reefs. Benthic microalgae, macroalgae and cyanobacteria communities will dominate these reefs although it is uncertain which species or taxa will dominate.
- Reef carbonate frameworks are likely to slowly disintegrate under vastly reduced calcification (due to elevated temperatures and decreasing pH) and the possible acceleration of bioerosion. Reefs will have less structure and hence reduced habitat complexity and holding capacity for reef organisms. It is not known how long these processes will take to have an effect on coral reefs.
- Reduced coral communities and reef structure will lead to a major reduction in reef biodiversity with some coral-dependent species going extinct.
- At longer time frames, negative reef maintenance and growth will mean that sections of the Australian coastline that are currently protected by reef structures like the GBR will gradually become more exposed to ocean wave stress. This may eventually have ramifications for the current distribution of coastal seagrass and mangrove communities.
- Intensified cyclone regime will increase physical impacts on coral communities and will accelerate the shift from high-diversity communities to assemblages dominated by few resistant massive/encrusting species. Reduced vitality of corals will mean that recovery will be compromised; further accelerating the shift of reefs away from coral dominated reefs.
- The increased intensity of flood events along with prolonged drought along east Australia will lead to periods of reduced water quality and flooding (with associated sediment, nutrients, and freshwater impacts) that will affect reefs further offshore.

### 10.3.3 Potential management responses

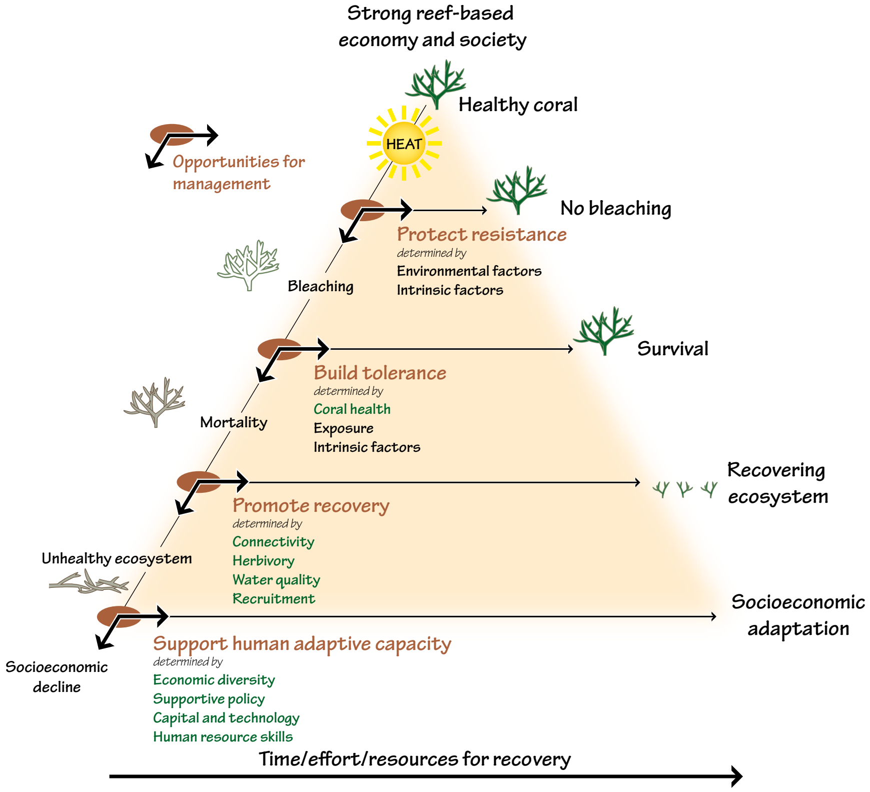
The most serious threats to corals in the context of climate change are coral bleaching caused by warming sea temperatures, and decreased calcification due to ocean acidification. Neither water temperature nor ocean chemistry is amenable to mitigation at the scale of local reef management. However, there is a variety of local factors that are can influence the susceptibility of corals to global stressors. An understanding of the process of coral bleaching, and the factors that influence outcomes

at various steps along the causal pathway, provides the basis for scientifically-based management strategies that aim to reduce the impacts of climate change on corals[149,135].

A similar analysis may be possible for ocean acidification in the future, once more is known about the interactions between aragonite saturation state and other (more local) factors that influence calcification in corals. Possible management strategies at the local scale could be measures to (1) increase pH to shift the aragonite saturation state, or (2) reduce wave regimes locally to protect patches of more susceptible morphologies from breakage. This could probably only be achieved in enclosed reef areas (eg micro atolls). However, it is unlikely that such attempts would be cost effective as a conservation strategy or as a rescue operation for tour operators.

Three conditions determine the outcome of stressful temperatures on corals: resistance, tolerance and reef recovery. Each of these offers a potential focus for management action aimed at reducing the impacts of coral bleaching (Figure 10.1). Damage to a coral community might be reduced if managers can influence or somehow enhance the effects of factors that determine the ability of corals to maintain their symbiotic dinoflagellates even when exposed to high temperatures (protecting resistance). Experiments to test the effectiveness of shading corals during periods of hot,

***Figure 10.1*** *The coral bleaching process, showing opportunities for management action to reduce the impacts of stressful sea temperatures on coral communities (from Marshall and Schuttenberg 2006)*



still conditions are an example of efforts to protect resistance at a very limited spatial scale. Managers may also be able to build the ability of corals to tolerate bleaching. In particular, recent research has shown that the lipid content of corals affects their ability to endure bleaching[9], suggesting that management strategies aimed at maintaining coral health (such as improving water quality) may play an important role in reducing the severity of coral bleaching. The part of the bleaching process most amenable to management action is the potential for coral communities to rapidly recover following coral mortality. Healthy habitats are better able to provide the conditions required for recruitment, survival and growth of new corals after bleaching has killed established colonies. In particular, good water quality, an abundant and diverse community of herbivores, and high coral cover are key aspects of ecosystem quality that should be priorities for reef management that aims to minimise the impacts of climate change on coral communities[199].

Although there are management actions that can reduce the impacts of coral bleaching, ultimately the fate of coral reefs will be determined by a combination of the rate of climate change, and their resilience to these changes. This suggests that immediate steps must be taken to reduce the sources of emissions that are driving climate change. In addition, the interaction of climate change impacts with secondary factors (eg water quality and fishing pressure) suggests some important strategies that need to be undertaken as climate change continues. These would build on the significant steps that have already been taken to improve the resilience of the GBR ecosystem, such as increasing the area of no-take zones from 5 to 33 percent, and developing a Reef Water Quality Protection Plan. Together, these measures have been hailed as being of international conservation significance. However, climate change poses additional and new challenges to tropical marine ecosystems, requiring further management efforts. Based on what is currently known about the risks from climate change, we offer the following recommendations:

- To minimise the risk of major degradation of coral reefs, global emissions need to be reduced so that atmospheric concentrations of $CO_2$ stabilise at levels no higher than 500 parts per million.
- Management effectiveness will be benefit from a thorough understanding of regional differences in vulnerability across all stresses. Hence, a more detailed understanding of the basis of tolerance in organisms like corals and their symbionts as well as a detailed 'vulnerability map' for the GBR can contribute substantially to resilience-building efforts.
- Reef resilience will also be improved through effective management of river catchments (ie reduced erosion potential of particulates, nutrients and toxicants) so as to improve coastal water quality and prepare for the impacts of more intense storms on an increasingly drought ridden coastline.
- Continued protection of healthy herbivore populations will help maintain and promote coral recruitment into disturbed areas.
- Explore the pros and cons of artificial structures to maintain reef species in areas where corals have been removed and the reef framework has disintegrated, or as stepping-stones between source and sink reefs in areas of low connectivity.
- Efforts to explore the effectiveness and costs of technologies to reduce climate impacts (shade structures, restoration technologies) should be facilitated for small areas of high natural or industry (tourism) value.

### 10.3.1 Further research

Our analysis reveals numerous gaps in our understanding of how corals and their dinoflagellate symbionts will survive under rapid climate warming and ocean acidification. Although we are rapidly improving our understanding of how corals are affected by thermal stress and acidification, we need to improve our understanding of how these conditions affect other important reef species, especially those that are important reef calcifying organisms (eg calcareous red algae). It is imperative that we pursue an understanding of the molecular basis for stress tolerance in corals and their symbionts. As the tools of the later exist, engaging in a national research program to achieve this must be a priority. We need to also expand our understanding of how climate change and ocean acidification will interact, both together and with other climate related factors (eg storm intensity). At higher levels of organisation, we need to improve our understanding of the consequences of the loss of corals as major community members on Australian reefs. In this regard, a regional 'vulnerability map' would be a valuable tool for understanding the interplay between local and global stresses in complex ecosystems like the GBR. Assessments are also needed of how reef biodiversity is tied to, and affected by, the abundance of reef-building corals. Equally, we need to know how projected changes in benthic community structure will affect commercial fish stocks, and to explore ways that we might ameliorate these changes (eg artificial reef structures). Other industries such as marine tourism (one of Australia's largest industries and export earners) will be affected by severely degraded coral reefs. Some analyses of this problem have been undertaken. Projections of vulnerability of these industries and reef usages, however, need to be coupled with socio-economic studies that examine strategies to reduce the impact and spread the risk to these industries of major changes in the appeal of coral reefs to visitors. Lastly, we need to understand better how changes in the health of tropical marine ecosystems in Australia's backyard (southeast Asia and the western Pacific) will affect the status of societies that depend on coral reefs for food and resources. In this respect, Australia needs to understand and be ready for potential impacts on the social and economic well-being of millions of people who depend for subsistence on the coral reefs in neighbouring countries.

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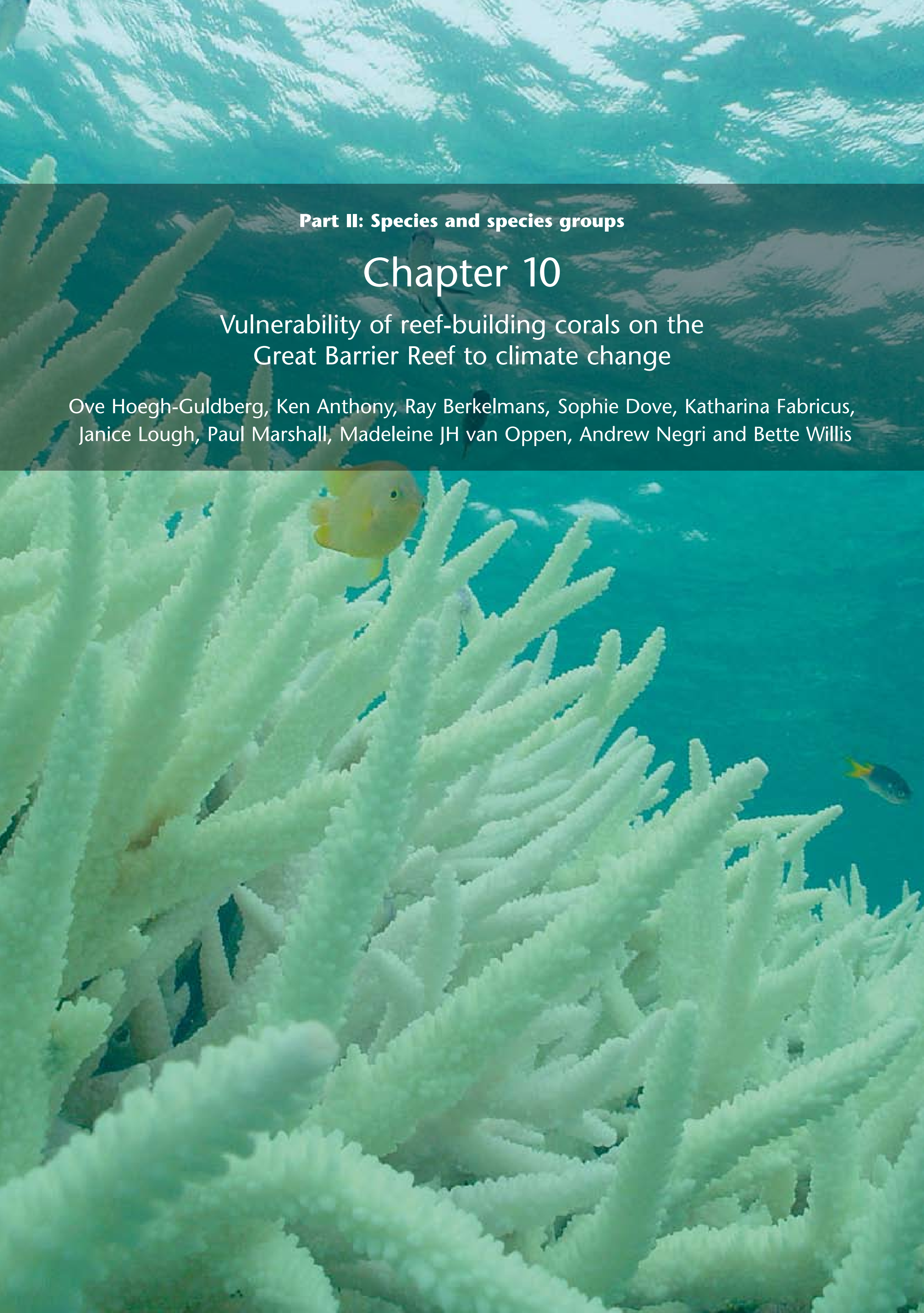
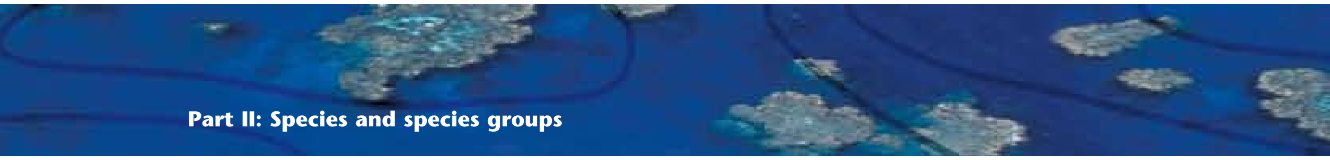


## Part II: Species and species groups

# Chapter 10

# Vulnerability of reef-building corals on the Great Barrier Reef to climate change

Ove Hoegh-Guldberg, Ken Anthony, Ray Berkelmans, Sophie Dove, Katharina Fabricus, Janice Lough, Paul Marshall, Madeleine JH van Oppen, Andrew Negri and Bette Willis



# 10.1 Introduction

## 10.1.1 Reef-building corals

Reef-building corals (Order Scleractinia Class Anthozoa) form extensive skeletons of calcium carbonate (limestone), depositing enough material over time to form vast reef structures that may be easily seen from space. The majority of reef-building corals are hard (stony) scleractinian corals. Many octocorals (especially soft corals in the family Alcyoniidae and the blue coral *Heliopora*) and some hydrozoan corals (such as *Millepora*) also contribute to reef-building. Corals form the framework of reef structures, while other organisms such as calcareous algae (especially red coralline algae) play a key role in cementing and consolidating the reef framework. This chapter focuses on the vulnerability of reef-building corals to climate change. The implications of climate change for macroalgae are covered in chapter 7 and a broader treatment of reef processes is provided in chapter 17.

## 10.1.2 The role of reef-building corals in the GBR

Major coral reefs stretch along both coastlines of the Australian continent, from Frazer Island to Torres Strait on the east coast, and from the Houtman Abrolhos reefs across the northwest coast of Australia to the western edge of the Gulf of Carpentaria on the western side of Australia. These coral reefs show a tremendous variety of structures within this broad geographical range, from poorly developed reefs that fringe inshore regions to extensive carbonate barrier reefs offshore. At more southern locations, coral populations form important communities despite the fact that temperature, light and the concentration of carbonate ions are such that there is no net accumulation of calcium carbonate. These reefs are referred to as non-carbonate coral reefs. Australian coral reefs provide critical habitat for a diversity of fauna and flora that includes over 400 species of corals, 4000 species of molluscs and over 1500 species of fish. The role of coral reefs in underpinning coastal economies in Australia is becoming increasingly recognised with the pristine nature of coral reefs being identified as the key driver of an internationally focused tourism industry. The contribution that the Great Barrier Reef (GBR) tourism industry makes, as part of regional tourism, to the Australian economy is A$6.1 billion per annum[86,1].

## 10.1.3 Critical factors for coral survival

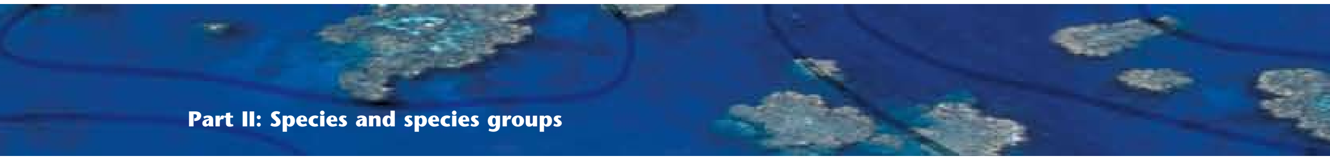
Corals have a symbiotic relationship with dinoflagellate protists (division Pyrrhophyta, class Dinophycaea, genus *Symbiodinium*), which are referred to loosely as zooxanthellae. The dinoflagellate cells of Symbiodinium exist within vacuoles in coral host cells, forming a close endosymbiotic mutualistic association. The dinoflagellates photosynthesise at rates similar to that of free-living dinoflagellate species but translocate up to 95 percent of the photosynthetic products to the host cell (reviewed in Muscatine[143]). The coral receives a range of products including sugars, amino acids and larger compounds such as lipids and small peptides. In return, the dinoflagellate symbionts gain access to a rich supply of inorganic nitrogen and phosphorus from the host, which supports the primary productivity of the dinoflagellate under the otherwise low-nutrient conditions typical of sub-tropical and tropical seas. The efficiencies of the internal recycling of nutrients with corals are considered to underpin their ability to build the vast reef structures found along tropical and sub-tropical coastlines.

Examination of the environmental conditions under which corals thrive today provides valuable insight into the sensitivity of corals to key environmental variables and to how they might respond under future climate change. Kleypas et al.[105] explored the environmental factors underpinning 6451 reef locations and identified several factors that were correlated with the distribution of coral reefs. In particular, they noted the strong correlation of carbonate reef systems with well-lit, warm (greater than 16°C) and saline (23 parts per thousand) waters with aragonite saturation states ranging from 3.28 to 4.06. Interestingly, coral reefs are found in a range of nutrient concentrations in contrast to common dogma that coral reefs are always found in low nutrient conditions. These conditions give us insight into the evolutionary limits of reef-building corals, which is important in understanding how corals might, or might not, be able to cope with the major environmental changes projected to occur over this century. This is particularly relevant to problems associated with the acidification of ocean waters caused by rising atmospheric carbon dioxide[94]. Under almost all future scenarios, changes in atmospheric carbon dioxide are likely to decrease the average aragonite saturation state of the world's oceans well below 3.0, the point at which most corals appear unable to form skeletons.

A great deal of research has been undertaken on the direct impacts of climate change on adult coral colonies. The effects on potentially sensitive reproductive processes, however, have received far less attention. Successful reproduction and recruitment is essential for ongoing survival of coral reefs, particularly following heavy disturbances such as bleaching, where recovery of coral abundance and diversity relies largely on recruitment by larvae or propagules from other coral communities[44]. Corals have two distinct strategies for reproduction: broadcast spawning of gametes and brooding of larvae[79]. The early life stages of corals (such as oocytes, sperm, larvae and recruits), as well as critical transitions in life history (fertilisation and larval settlement), may be just as susceptible to thermal stress as mature colonies.

There are many other factors that influence the survival of corals. Poor water quality, such as high nutrient levels and sedimentation rates, can have dramatic influences on corals and the reefs they build. Coral reefs change and diminish as they approach coastal areas typified by natural coastal runoff and flooding events[187]. In recent times, coastal development has increased the amount of sediment flowing off the land[132], adding agrichemicals and other pollutants. Decreasing light levels, increased sediment levels and increasing levels of pollutants can reduce coral growth and in some circumstances have removed coral communities from reefs altogether[188]. Storm frequency and intensity also influences coral reefs, through natural events that may remove corals temporarily from some areas. Natural disturbance events like storms are considered to play an important role in mediating the strong competitive forces that may end up excluding less competitive species.

Discussion of how environmental factors determine the distribution of reef-building corals is important basis from which to explore the vulnerability of reef-building corals and their dinoflagellate symbionts to climate change. The next section focuses on such vulnerability within the context of thresholds, specifically with respect to those factors that appear to play a key role in determining the distribution of corals. In addition to dealing with issues of stress exposure, the sensitivity and potential impacts of these factors will also be considered.



# 10.2 Vulnerability of corals to climate change

## 10.2.1 Changes in water temperature

### *10.2.1.1 Exposure – water temperature*

Average water temperatures of the GBR are now significantly warmer than at the end of the 19th century, 0.4°C warmer based on 30-year averages (Lough chapter 2). Rates of warming of Australia's tropical and sub-tropical waters are similar to that seen globally for tropical waters (+0.17°C from 1951 to 1990[126]). As with changes in global temperature, these changes are unprecedented in terms of rates of change seen over the past several hundred[128] if not several thousand years. Warming seas have pushed corals ever closer to their thermal maxima, with the result that warmer than average years (part of natural variability) now push corals beyond their thermal tolerance[82].

### *10.2.1.2 Sensitivity – water temperature*

The most dramatic manifestation of corals being pushed beyond their thermal tolerances is coral bleaching, which is a condition in which corals lose the brown pigmentation of their dinoflagellate symbionts. Coral bleaching is essentially a stress response in corals that arises as the intricate endosymbiosis between animal and single-celled plant begins to break down.

Corals will bleach in response to a range of conditions including high or low irradiance[186,201,88,71,121], elevated or reduced temperatures[97,98,40,88,76,169,90], reduced salinity[103], the presence of some toxins (eg cyanide[100], copper ions[99], herbicides[147] and microbial infection (eg Vibrio[110]). Bleaching in response to isolated and local-scale (1 to 500 metres squared) stresses has been reported for at least 70 years[201].

Sensitivity of corals to thermal stress can be highly variable between species[134,129,185], between populations within species[75,22,185] and at spatial scales ranging from centimetres to thousands of kilometres. Some of this variation in sensitivity in space may be due to environmental factors such as differential light regimes[40], water motion[144] and thermal micro-, meso- and macroclimates. However, a number of biological factors also play a significant role in the sensitivity of corals to temperature. The symbiont type associated with corals in particular has been shown to greatly influence thermal tolerance with so-called type D symbionts conferring an extra 1 to 1.5°C tolerance in *Acropora millepora* compared to type C2[22].

Thermal sensitivity at the coral species level is likely to be shaped in large part by host factors that govern which symbiont types form stable symbiosis with particular species, the strength of association under stressful conditions and the flexibility of the symbiosis. Some of the differential sensitivity to thermal stress among species and populations may be due to biochemical processes. For example, enzymes involved in antioxidant functions such as copper/zinc superoxide dismutase and manganese superoxide dismutase and molecular chaperones such as heat shock proteins Hsp60 and 70 and chlorophyll Hsp have been shown to play a role in the defence against thermal stress in either or both animal hosts and symbiotic algae[29]. Similarly, mycosporin-like amino acids produced by coral hosts have been shown to provide protection against damaging ultraviolet (UV) radiation during hot, still conditions[54,137]. The role of fluorescent pigments in the photo-protection of corals during bleaching is less clear. These pigments are more common in corals in high light environments, such as reef flats, and are clearly involved in shading corals and their symbionts from excessive light levels[51,167]. They are also a diverse group of pigments with a range of functions that do not necessarily include reduced

sensitivity to bleaching[50]. These protective and reparative mechanisms are also evident in coral eggs and larvae[139] and may influence differences in sensitivity to thermal stress between species and life history stages.

### *10.2.1.3 Impacts – water temperature*

Mass coral bleaching events are triggered by warmer than normal conditions, a strong relationship as seen by the fact that mass bleaching events can be predicted using simple sea surface temperature anomalies measured from satellites and time-integrated temperature curves[21,82]. Light is an important co factor. Corals that are shaded do not bleach as severely as those under normal irradiances[100,142,9] which is a consequence of the mechanism that involves an increase in the sensitivity of the symbionts to photoinhibition[100,82]. The water flow field also appears to be important[144,145] and can greatly impact the photosynthetic performance of zooxanthellae *in hospite*[184], with corals that are in still as well as warm and sunlit conditions experiencing the greatest coral bleaching. This experimental outcome supports some of the initial observations of coral bleaching, which coincided with the doldrums that are typical of El Nino years in some coral reef regions[74].

Coral bleaching is not always fatal, and the outcome for the coral is dependent on the level of stress. Bleached corals may recover their symbiotic dinoflagellate populations following a bleaching event if the stress conditions are mild and short-lived. It may take several months for the dinoflagellates to repopulate the tissues, a process that arises from populations of dinoflagellates remaining in the host tissues. Often corals that appear bleached have as many as 10,000 dinoflagellates per centimetre squared[88] which is two to three orders of magnitude less that than that seen in healthy corals but more than enough to initiate re-infection from within. Mortality of corals will occur if conditions are warmer for longer periods, most likely because the symbiosis reaches a critically low energy status as the symbiont population continues to decline[9]. In some cases, mortality will increase to include most corals growing within a population, reef or region[82].

Australia's coral reefs have bleached repeatedly over the past 30 years, with events occurring in 1980, 1982, 1983, 1987, 1992, 1994, 1998, 2002 and 2006[150,82,20,24]. Large sections of the GBR have bleached during these years, with impact measurements supporting the conclusion that events in 1998 and then 2002 were the worst on record. Fortunately, mortality rates have been relatively low because the conditions have not been as severe as in other parts of Australia and the world (eg western Indian Ocean in 1998, 46% mortality of corals[68]). Scott Reef in the northwest waters of Australia, for example, has not been so lucky. In 1998, a very warm core of water persisted above the oceanic, and normally well flushed, Scott Reef for several months. This resulted in almost total bleaching and mortality of corals down to 30 metres. Recent reports indicate that recovery of these reefs has been slow[140], with the percentage cover of corals still very low compared to that seen before 1997. Additional bleaching in 2003 and a category 4 cyclone in 2004 have removed further corals from the remaining populations.

Not all coral species are equally susceptible to thermal stress[87], a factor that may be important in shaping the structure of future coral reefs. Following the 1998 bleaching event on the GBR, Marshall and Baird[134] demonstrated that bleaching susceptibility varies dramatically among coral taxa on the GBR: acroporids and pocilloporids were severely affected (18 to 38% mortality), poritids and faviids were moderately affected and genera such as *Turbinaria* and *Galaxea* were largely unaffected.

Interestingly, this pattern is consistent with the general pattern of species distributions across the GBR lagoon, with acroporids and pocilloporids increasing in abundance towards offshore locations and *Turbinaria* and poritids (in particular *Goniopora*) often dominating inshore reefs[46] often characterised by higher temperatures[21] and high turbidity[6]. Tentatively, increased frequency and intensity of thermal anomalies on the scale of the GBR may push most species of acroporids and pocilloporids beyond their thermal niche boundaries (ie threshold for sustained growth, reproduction and survival). Mid-shelf reefs may experience the largest changes in community composition as intensified runoff scenarios due to stronger cyclones mean that these reefs may occasionally experience high-turbidity regimes reminiscent of inshore reefs today.

Where thermal stress has resulted in significant mortality, coral community composition has often also radically changed as a result of the variable sensitivity of different species to stress. In the Palm Island Group in the central GBR for example, declines in coral cover of between 10 and 80 percent after the 1998 bleaching event were largely due to loss of dominant *Acropora* spp.[20,176]. Some species such as *Acropora pulchra* suffered local extirpation and other species such as the fire coral *Millepora* spp survived only as a few colonies growing in deeper water. Macro-algae increased to become the dominant cover on some of these reefs thus bringing about a community phase shift. This is a familiar pattern of community change echoed in Indian Ocean and many other reef provinces around the world after the 1998 global bleaching episode[197].

Increased water temperatures have the potential to affect both the reproductive output of parental colonies and the success of early coral life stages. Photosynthetic products are critical to coral gametogenesis and larval production[160] and bleaching during the typical eight-month period of gamete development[79] may negatively affect reproduction. Bleaching prior to or during gametogenesis can result in low testes and egg numbers along with smaller than usual eggs[192] and incomplete gametogenesis[177]. *Acropora* spp. that were affected during the 1998 Okinawan bleaching event also exhibited reduced fertilization in laboratory experiments performed nine months later[151]. Soft corals bleached in the laboratory were affected in a similar way, exhibiting reduced fecundity and fertilization failure over two reproductive cycles[138]. Larvae from these bleached colonies were lower in lipids, proteins and carotenoids compared with unbleached individuals[139]. Coral reproduction can also be directly affected by increased water temperature, with laboratory experiments indicating incomplete fertilization and more rapid (but often abnormal) embryogenesis as temperatures increase[19,18,147]. High water temperature can negatively impact larval development rates and the symbiont density in zooxanthellate larvae[58] and the settlement and survival of azooxathellate larvae[18]. Interestingly, high water temperature in the Virgin Islands was shown to correlate with higher numbers of juvenile corals, but this was accompanied by greater mortality rates[57].

#### *10.2.1.4 Adaptive capacity – water temperature*

The preceding discussion is built on the premise that the behaviour of corals to thermal stress does not change on the same time scale of anthropogenic climate change. In this regard, it is important to consider the potential for corals to acclimatise (a phenotypic change within the individual) or to adapt (a genetic response at the population level) to thermal stress. There is no doubt that corals, like other animals and plants, acclimatise to changes in their environment including seasonal temperature changes[27,66,39]. Berkelmans and Willis[23], for example, found that the winter maximum upper thermal limit for the ubiquitous coral *Pocillopora damicornis* was 1°C lower than the threshold for the same

species of coral in summer. Nakamura et al.[146] have made similar observations for corals on reefs in Okinawa. Acclimatisation in this regard can occur in a range of cellular mechanisms and at a series of time frames[39]. As with any physiological trait, however, there are limits to the extent to which organisms can acclimatise to environmental change. Berkelmans and Willis[23] observed that corals have some potential to acclimate to seasonal differences in temperature. However, they have little capacity to acclimate to temperatures greater than 2–3°C above mean summer maxima, at least in experimental heating trials[20]. The observation of increasing (as opposed to decreasing) mortality rates among coral communities over the past 25 years also suggests that acclimatisation by corals to higher temperatures in the summer may have already been largely exhausted[82,68,69].

One of the ways in which reef-building corals may be able to acclimatise is by changing a thermally sensitive *Symbiodinium* type for one that is more thermally tolerant, an idea first put forward by Buddemeier and Fautin[32] as the Adaptive Bleaching Hypothesis. There are various interpretations of this hypothesis, and there has been active discussion in the literature over its definitions and whether or not there are data to support the elements of the hypothesis[89]. As yet, there is no evidence of exogenous uptake of new symbiont types by adult scleractinian corals although Lewis and Coffroth[123] provided some evidence for exogenous uptake by adult octocoral colonies (note: problems with the contamination of controls in this study throws some doubt on the conclusions however).

There are, however, several examples of multi-cladal associations (coral hosts that contain more than one genetic variety of *Symbiodinium*) that shift the dominance of one genetic variety over another[15,179,178,22]. These shifts in dominant genotypes as a function of environmental conditions suggest that some genotypes may be more suited to new environmental conditions. For example, Berkelmans and van Oppen[22] provided experimental evidence that *Acropora millepora* corals with multi-cladal assemblages can change the dominant symbiont type from *Symbiodinium* type C2 to D and can increase their thermal tolerance as a result. This type of change is a form of acclimatisation, because it represents a shift in the dominance of dinoflagellates that have had a pre-existing endosymbiotic relationship rather than the evolution of new symbiotic associations and also because in most instances the changes on the dominant *Symbiodinium* are not passed on from one generation to the next.

A distinction is drawn between *shuffling* and *switching* of symbiont types where the mechanism of acclimatization is due to the flexibility of coral-*Symbiodinium symbiosis*. Shuffling is a quantitative (compositional) change in the relative abundance of symbionts within a colony whereas switching is a qualitative change involving symbionts acquired from the environment. The latter exogenous symbionts may represent types that are new to the colony but not the species, or may be truly novel to the host species. In the latter case, the term 'evolutionary switching' is appropriate. The latter is used to explain changes in the symbiont distribution within hosts in response to stress. Evolutionary switching, however, is considered an extremely rare event and hence is unlikely to play the ecological role that some authors have claimed (eg Baker[15]).

In addition to understanding the limits to the flexibility of coral-*Symbiodinium* symbioses relative to ecological timescales, there has been a growing interest in defining the functional nature of the differences between *Symbiodinium* genotypes. In this respect, the range of genotypes of *Symbiodinium* dinoflagellates that inhabit corals[181,182,16,125,164,117] is correlated in some instances with light, temperature and stress. Some genetic varieties such as clade D are clearly correlated with warmer and putatively more stressful habitats than most types of clade C[183,166,185]. Growth in corals is also clearly influenced by symbiont type. Little et al.[124] showed that juvenile *Acropora millepora* and *A. tenuis* corals grow faster with *Symbiodinium* clade C compared to those associating with clade D. These types of studies are important in that they explore the functional responses of *Symbiodinium* strains that are otherwise only distinguished by the non-coding segments of their genomes. Future studies need to focus on how the growth, reproduction, thermal tolerance and mortality of corals are influenced by the strain or sub-cladal level of symbiotic dinoflagellates that they contain.

### *10.2.1.5 Vulnerability and thresholds – water temperature*

Isolated examples of coral bleaching have been recorded for many years. Reports, however, of entire communities and reefs bleaching (otherwise known as mass coral bleaching) have only been reported in the scientific literature over the past 30 years. In these cases, coral bleaching may affect up to 100 percent of the reef-building corals in a community. The first examples of mass coral bleaching occur in the scientific literature in the early 1980s[200,72,150], and since that time, mass coral bleaching has increased in frequency, intensity and geographical extent[82].

Some of the most spectacular examples of how mass coral bleaching can eliminate corals from a reef or region occurred during the 1997–1998 global event. In this event, which began in late 1997 in the eastern Pacific and spread across the world by the end of 1998, coral reefs in most parts of the world experienced mass coral bleaching. Some reefs, however, experienced only mild effects of bleaching and recovered within a few months. Other reefs, however, experienced severe coral bleaching that was followed by mass mortality. In regions like the Seychelles, Maldives, Okinawa and Palau, mortality of corals reached over 80 percent[82,196,77]. Some of these sites have recovered significantly. It is important to note that some regions still have much less coral than they had before the 1998 bleaching event[69] and hence the term 'recovering' needs to be qualified in most if not all cases.

Elevated sea temperatures are the primary cause of mass coral bleaching – a fact that is extensively supported by field and laboratory studies[26,82,120]. These data highlight the existence of thermal thresholds that vary with geographic location, species, genotype, physical factors (eg light, salinity) and history[41,56,99,82,23,21,28]. Despite this secondary source of variability, satellite measurements of sea surface temperature anomalies can still be used to predict bleaching events several weeks in advance with greater than 90 percent accuracy at large scales[82,175]. There is considerable additional information that can be derived as to the severity of the outcome of thermal stress if the time-period of exposure above threshold levels for a coral reef is also considered. High resolution time-temperature curves developed from *in situ* temperature data after the 1998 bleaching event[21] proved highly effective in predicting bleaching on the GBR in 2002 and 2006. Similarly, the Degree Heating Week (DHW) index developed by Strong et al.[175] is the multiple of exposure intensity (degrees above the threshold) and time, and has been highly successful in predicting mass bleaching events[a]. In the 1997–1998 global bleaching event, for example, coral reefs that experienced Degree Heating Month (DHM; a variant on DHW) values of less than 1.5°C per month largely recovered while those that experienced DHM values of 3°C per month or more experienced large scale mortalities[83].

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[a] Hotspot program, coordinated by the National Oceanic and Atmospheric Administration, NOAA. http://orbit-net.nesdis.noaa.gov/orad/coral_bleaching_index.html

Projections of how changing sea temperatures will impact Australia's coral reefs reveal that sea temperature may soon exceed the thresholds for coral bleaching on a yearly basis[82,48,49]. Based on how corals respond to increased temperatures today, an increase of 2°C in the average sea temperature in tropical and subtropical Australia will lead to annual bleaching with up to 97 percent of reefs affected and will almost certainly result in regular large-scale mortality events[82,84,24]. This is confirmed if one integrates the DHW index of Strong et al.[175] into the projections of how communities of corals will respond to thermal stress events that are hotter and longer in the future. Most evidence indicates that, for the majority of corals, huge increases in mortality will almost certainly ensue[85].

Models of how the expected changes in mortality will impact the abundance of coral communities indicate that even small changes in mortality regime may lead to large changes in the distribution and abundance of corals on the GBR. These changes have been examined geographically on the GBR by Done et al.[48], who modelled the probability of mild to severe bleaching events, and how recovery of such aspects as the aesthetic appeal of coral reefs interact within mild and severe climate change scenarios. Done et al.[48] found that the return time of devastating mass coral bleaching events even under mild warming scenarios was such that the ability of coral reefs to recover and maintain significant coral communities was severely compromised. The conclusions of their study support those of Hoegh-Guldberg[82] and suggest that the deterioration of coral populations is highly likely under most of the scenarios examined by Done et al.[48]. The debatable issue of rapid genetic adaptation, which may modify some of the conclusions of these two studies, will be discussed presently.

Successful reproduction and recruitment is essential to ensure the long-term survival of coral reefs, particularly following heavy disturbances such as bleaching[44]. Reef-scale sub-lethal bleaching is likely to lead to the widespread failure of gametogenesis[117,192] and a subsequent reduction in the recovery disturbed reefs. This secondary impact may persist over several reproductive seasons and[138] as corals prioritise their energy balance towards colony repair and maintenance rather than reproduction. The only study to directly measure fecundity on GBR corals following bleaching documented widespread reductions in egg number and size across several *Acropora* and *Montipora* species[192]. Direct comparisons between the sensitivity of adult corals and their early life stages to thermal stress have not been made for GBR species. *Diploria strigosa* larvae from the Gulf of Mexico, however, exhibited reduced settlement and increased mortality following a weeks exposure to seawater temperatures of between 30°C and 32°C, just 1 to 3°C above the ambient seawater temperature of that region[18]. This result indicates that the early life histories of coral may be just as vulnerable to direct thermal stress as adult colonies, even in the absence of symbiotic dinoflagellates. The severity of response is likely to vary between species, and recruitment following bleaching events may be skewed towards those species that are more tolerant to bleaching, further accelerating phenotypic change across reefs.

### 10.2.2 Changes in light and ultraviolet radiation

Light is obviously of key importance to coral reefs as it drives photosynthesis and powers calcification providing both the organic matter and the calcium carbonate foundation that defines coral reefs. Photosynthesis is however a dangerous process in that it involves the capture of light energy by chlorophyll and other phytopigments and generates a flow of electrons at the same time as it generates oxygen ($O_2$), a ready acceptor for those electrons. The potential danger lies in the creation of singlet oxygen due to the interaction of chlorophylls that are unable to off-load their excitation energy with $O_2$, and the production of other forms of reactive oxygen species such as superoxide anions ($O_2^-$) as $O_2$ accepts electrons that are unable to be processed by electron transport to carbon dioxide ($CO_2$) fixation[148]. The wavelengths of light that drive photosynthesis (photosynthetically active radiation) overlap the visible range and hence the pigments that capture this energy are also visible to humans. Shorter, more energetic wavelengths, (300 to 400 nanometres) also make it through the earth's atmosphere and are referred to as ultra violet radiation (UVR). The dangerous consequences of UVR are well known, most notoriously through the accepted causal role UV plays in the formation of skin cancers. UVR leads to indirect damage through its interaction with photosensitisers like chlorophyll leading to lipid peroxidation and DNA strand breakage. UVR can also directly damage DNA leading to structural changes that inhibit DNA replication and protein synthesis. The presence of UVR however has also been associated with positive morphogenic responses that enable plants to deal with other frequently co-occurring environmental stresses[70].

Light reaching the earth surface is attenuated in the atmosphere. Ozone plays the major role in attenuating UVR, and clouds (water vapour), dust and gases significantly attenuate photosynthetically active radiation and infrared radiation. Observations of decreases, about 3 percent per decade, in the global ozone, and increases in atmospheric $CO_2$, leading to changes in weather patterns that have a potential to alter cloud patterns can therefore significantly affect the intensity and quality of light attaining the earth's surface.

### 10.2.2.1 Exposure – light and ultraviolet radiation

All reefs witness variability in light associated with diurnal patterns and differential cloud cover. At low latitudes, reefs are additionally affected by seasonal variability in light intensity. The water column attenuates light exponentially both by absorbing and scattering photons resulting not only in a reduction in the intensity of light with depth but also a change in quality due to the preferential absorption and scattering of red and infra-red photons. Even in crystal clear tropical waters, most of the red photons are absorbed within the first few meters of the water column with the implication that shallow water corals living in regions experiencing large tidal fluxes not only witness changes in intensity but also changes in light quality that may have substantial effects on photosynthesis. Particles in the water column such as phytoplankton and suspended sediments further attenuate and alter the spectrum of light. Highly turbid water may reduce benthic irradiance to critical light levels, compromising rates of photosynthesis for organisms like corals and marine plants[7,8]. Conversely, given that light intensity is a measure of the number of photons passing through a fixed area in a set period of time, the shape of waves and the presence of diffuse or reflective surfaces can amplify the intensity of light by trapping or focusing photons in a specific area. This phenomenon has been shown to occur frequently in shallow lagoonal waters, and has been argued to occur between the branches or even within the tissues of reef building corals[60].

### 10.2.2.2 Sensitivity – light and ultraviolet radiation

The light intensity experienced by most photosynthetic organisms is neither constant in the short term (minutes to hours), nor constant in the long term (days to months). An imbalance between the amount of light energy capture and the ability to process that energy leads to the formation of damaging oxygen radicals. However, inadequate capture of light energy leads to scenarios where respiration (or metabolic activity) rates exceed photosynthetic rates impacting on growth and reproduction.

To maximise growth and limit damage, photosynthetic organisms therefore tend to optimise their ability to capture and process light energy to the prevailing environmental light regimes. The outcome is that some photosynthetic organisms are high light specialists, while others are low light specialists, with a few that are flexible enough to accommodate a large range of light intensities. The ability to accommodate a range of light intensities is genetically set by the ability to express proteins that allow for the restructuring of the antennae or the electron transport chain[148]. A photosynthetic organism that can handle two light extremes will appear bleached under the high light environment compared to the low light environment due to having expressed proteins that bind less chlorophyll. In contrast, a low light specialist will look bleached in the high light field due to the photo-oxidation of the antennae due to the activity of accumulated singlet oxygen on the histidine ligands that bind the pigment to the protein template. Bleaching in the latter case is more likely to result in mortality[2].

In corals, dinoflagellates sit within the symbiosome (vacuole) membrane of the coral host cell. These symbiont-containing host vacuoles may be stacked on top of each other within the coral gastroderm leading to a highly heterogeneous light field where deeper dinoflagellates are significantly shaded[61]. The host cell may contain flexible pigment-proteins that modulate not only light intensity but also spectral quality[52] (J Deckenback pers comm). The host may place dinoflagellates within tentacles that can be exposed or withdrawn based on specific spectral cues[122]. Alternatively, the host may alter its skeletal morphology to trap light effectively and reduce the effect of self-shading[143,8,60] or even maintain fewer symbiotic dinoflagellates to limit self-shading at the expense of dinoflagellate respiration. As these mechanisms have been uncovered, there has been an increasing awareness of the multiple mechanisms that may be in operation even within a single species with no two individuals resorting necessarily to the same set of solutions.

In addition to host variability, there is considerable variability among genetically distinct varieties of *Symbiodinium*. Cultured *Symbiodinium* have been classified as high, low light specialists or generalists according to their ability to restructure their antennae[92]. Genetically distinct *Symbiodinium* have been found to occupy light associated niches within a coral branch[166], yet there are examples of very tight coupling between symbiont and host genotypes[116]. More often than not corals transplanted from one light environment to another undergo changes to the concentration of chlorophyll per dinoflagellate cell, rather than in the number of dinoflagellate cells present[61,88,64]. However, this is not always the case with some host colour morphs experiencing no change in dinoflagellate chlorophyll or cell concentrations, but rather compensating changes in host pigmentation (S Dove unpublished data). In some instances, upon transplantation, coral hosts maintain a specific symbiont genotype despite the fact that conspecifics in the new light regime host a distinct symbiont genotype (E Sampayo pers comm). The flexibility associated with accommodating changing light regimes can therefore lie with a flexibility to express physiologically different *Symbiodinium* or with flexible symbiont or host gene expression.

Changes in light quality as opposed to quantity can have a significant effect not only on photosynthesis but also on a range of processes that are essential for maintaining healthy reproducing organisms. These include the setting of circadian clocks and the induction of defensive strategies. In higher plants, light quality plays an important role in balancing photosystem II and photosystem I (PSII/PSI) dynamics with the consequence that plant photosynthesis is most efficient when plants are illuminated with light of similar spectral quality to that in which they were grown[190,189]. Pigments such as red light sensitive phytochromes and blue light sensitive cryptochromes are involved in setting the circadian clocks. In addition to this role, phytochromes shift between active and inactive forms in response to different wavelengths of light, particularly red (which is absorbed by photosynthetic organisms) and a red irradiation. These wavelengths provide proximity meter for shade avoiding plants to grow and project into regions of un-attenuated light[173]. Photolyases that repair certain types of UVB damage to DNA are induced by blue or UVA light[141].

The role of different wavelengths in stimulating behaviour or genetic response in corals is less well characterised. Levy et al.[122] showed that some coral species retract their tentacles in response to both blue and red light, while others only respond to blue light, and others do not respond at all. Kinzie and Hunter[104] showed that in comparison to red and green light, blue light stimulated increased chlorophyll a densities in corals, arguing that the relative proportion of blue light increases with depth and hence signals reductions in overall light intensities that necessitate improving the light capturing ability of the antennae. While corals and their symbionts are able to synthesis cryptochromes and photolyases (R Reef pers comm), their functional roles are yet to be elucidated. Photosynthetic action spectra have been provided for some, principally non-symbiotic, dinoflagellates[158]. The specific action spectra of PSI, isolated from PSII has yet to be determined for *Symbiodinium* making it difficult to access whether changing spectral quality can result in an imbalance PSI/PSII dynamics.

Reductions in cloud cover and depletions in the ozone layer increase the UVR dose to which organisms are exposed. In clear tropical waters, UVR is principally attenuated by the presence of dissolved organic matter with UVB reduced to 1 percent of surface irradiance by a depth of approximately 11 metres[55]. In response, most organisms have developed mechanisms to either protect themselves from UV damage, or repair DNA damage as it occurs. Protective mechanisms for organisms that are sessile usually involve the production of mycosporine like amino acids (MAAs), compounds that have high extinction coefficients in the UV. These compounds are abundant in corals above 10 metres, and are believed to originate from host diet or be translocated from their endosymbiotic dinoflagellates[54,108]. DNA repair mechanisms either use specific enzymes (photolyase) that harness light energy to reverse DNA damage, or involve a group of genes (nuclear excision and repair genes) that cooperate in the removal and replacement of damaged DNA. The ability of corals and dinoflagellates to repair UV damaged DNA is yet to be explored. While the ability to synthesise MAAs was initially only linked to clade A *Symbiodinium*[17], this may be because only a few clade C *Symbiodinium* were analysed in this study, subsequent investigation has shown that some clade C *Symbiodinium* also appear to contain MAAs[63].

Given that much DNA damage occurs indirectly through the creation of reactive oxygen species due to the interaction of UVR with photosensitisers in an oxygen rich environment, antioxidants play a major role in limiting damage. Both the host and the dinoflagellate may contain photosensitising pigments. Chlorophyll is the most abundant photosensitiser in photosynthetic organisms. Significantly, another fluorescent photosensitiser (named appropriately *killer red* for its ability to kill bacteria is an all protein chromophore isolated from a hydrozoan and which is structurally similar to the range of proteinaceous GFP-like compounds) that have been identified within the pigmentation of corals[33]. Interestingly, pigments can also act as effective antioxidants as is best exemplified by carotenoids. As yet, the full range of antioxidants available to either host or symbiont is yet to be determined, it may even turn out that while some GFP-like compounds expressed by hosts are photosensitisers potentially mediating the appropriate defensive response to increases in photon flux density, others may act as antioxidants (M Lesser pers comm).

### *10.2.2.3 Impacts – light and ultraviolet radiation*

Global weather patterns are changing. This is specifically true of southeast Queensland in Australia where drought conditions persist and are infrequently broken up by heavy rainfall. Correlated with these drought conditions is an observed increase in the number of cloud free days over the southern GBR (M Nunez, pers comm). Sustained insolation increases sea surface temperature and places additional stress on photosynthesis as existent pools of antioxidants and other defensive pools are used up. Infrequent and heavy rainfall is also undesirable for communities of corals as it leads to turbid freshwater flood plumes that can drastically attenuate light in the water column[7].

Additionally, the formation of low temperature cloud particles in the stratosphere provide the surfaces required by reactions, which catalysed by light, that lead to the destruction of ozone. This phenomenon is observed every spring over Antarctica as clouds formed in the winter are exposed to solar radiation. The stratosphere is believed to be cooling as a result of climate change because green house gases trap heat in the troposphere and prevent its escape to the stratosphere. There is therefore a growing concern that climate change may result in an exponential increase in global levels of UVB.

### *10.2.2.4 Adaptive capacity – light and ultraviolet radiation*

It is difficult to access how corals and their endosymbionts will respond to exponential increases in UVR, given that we do not know whether they have DNA repair mechanisms in addition to MAAs and an antioxidant defence mechanism. Given that increased and sustained light stress, at least in the Southern portion of the GBR, appears to co-occur with increasing temperature, it is necessary to ask how stable MAAs and this antioxidant defence system are at elevated temperatures. The answer is perhaps not so promising. Lesser et al.[121] found an inverse correlation between temperature and host tissue MAA concentrations. Equally, if the flexibility to handle high light is dependent on either the symbionts or host ability to acclimatize to the changing light field then it must be hoped that elevated temperature does not interfere with this ability. Experimentally, it has been shown that increasing temperature in a low light field decreases the concentration of the xanthophyll pool, potentially limiting the ability of *Symbiodinium* to divert excess excitation energy to heat[53]. Similarly, it has been demonstrated that while some forms of host pigmentation appear to correlate with increased photosynthetic performance at lower temperature, corals that are able to express these protein-pigments in high concentrations die as threshold temperatures are attained[50]. Threshold temperatures have been correlated with a reduction in mRNA concentrations for genes encoding these proteins[171].

Conversely, however it has been shown that corals that have been exposed in the long term to high light fields cope better (lose fewer symbionts) with increases in temperature[29]. Closer analysis showed that the host rather than the symbiont antioxidant system was most active on the high-light surface of the coral, although dinoflagellates on the sunlit side of the coral had a significantly larger xanthophyll pool[30]. An examination of the literature shows that few *Symbiodinium* cultures have been trialled for both heat and light tolerance. Of the few, the exclusively high-light adapted A2 *Symbiodinium* from *Zoanthus* sp. is able to tolerate relatively high temperature. The high- and low-light flexible A1 *Symbiodinium* from *Cassiopeia* sp. is intolerant of high temperatures[92,93]. Perhaps the message is that if a symbiont is already expressing defence mechanisms that enable it to deal with increased excitation pressure at PSII, then it can survive a limited additional amount of excitation pressure generated by temperature stress. However if the appropriate defence mechanisms have not previously been induced, then temperature stress above a given threshold will not enable them; despite having potentially enabled key enzymes in the water-water cycle[121].

In this context, the massive amplification of light within the tissues of corals that is predicted to occur during a severe bleaching event, due to the trapping of unimpeded photons by the diffuse and reflective skeletal surface of a scleractinian coral may account for coral mortality[60]. The scenario has been referred to as *photon hell*, which may be appropriate given the lethal doses of UVR or photosynthetically active radiation that are likely to be generated for host and remaining symbiont cells alike.

### 10.2.2.5 Vulnerability and thresholds – light and ultraviolet radiation

Corals show high sensitivity to light and UVR levels. This sensitivity increases under thermal stress due to blockages of electron flow through photosynthesis, essentially pushing thresholds for light exposure downwards. Increases in light and UV are occurring in tropical and subtropical Australia. These changes, however, are small. Under conditions in which climate change is not occurring, corals are only vulnerable to changes in light and UV to a small extent. This changes dramatically, however, as waters warm. Dramatic changes in the vulnerability of corals and their dinoflagellate symbionts occur as climate change occurs. The demonstration that thermally stressed corals bleach less and survive better if they are shaded during thermal stress reinforces this conclusion, and also suggests that some small scale technologies (eg shading) may successfully reduce the impact of thermal stress on local coral assemblages.

## 10.2.3 Changes in ocean chemistry

### 10.2.3.1 Exposure – ocean acidification

The present-day chemistry of the oceans is fundamental to the ability of reef-building corals to calcify and hence form the massive calcium carbonate framework of tropical coral reefs. The oceans have absorbed at least one-third of the excess $CO_2$ produced by human activities that has entered the atmosphere[159,107]. On entering the ocean, $CO_2$ reacts with water to form carbonic acid, which dissociates to form bicarbonate ions and protons. These protons react with carbonate to form bicarbonate, moving the ionic equilibrium from carbonate to bicarbonate as more $CO_2$ enters the ocean[159]. As the oceans take up $CO_2$, ocean pH and the saturation states of carbonate minerals (calcite, aragonite and high-magnesium calcite) decrease. These minerals are fundamental to the formation of skeletal structures in many marine calcifying organisms such as corals. The reduced carbonate ion concentration significantly reduces the ability of reef-building corals to form their skeletons and hence the reef structures that house hundreds of thousands of marine species.

### 10.2.3.2 Sensitivity – ocean acidification

The decrease in carbonate ions represents a major problem for calcifying organisms such as corals given that the rate of calcification varies linearly with the carbonate ion concentration[118,159]. Various lines of evidence indicate that coral calcification rates will decrease and carbonate dissolution rates

increase as the calcium carbonate saturation state decreases. Several controlled experiments of calcification rates under elevated $CO_2$ levels confirm that calcification rates decrease with increasing $CO_2$ levels. These measurements suggest that calcification rates may decrease by up to 60 percent with a doubling of atmospheric $CO_2$ concentrations by end of 21st century. This may put reef structures into net erosion with long-term implications for coastal protection[85].

### *10.2.3.3 Impacts – ocean acidification*

Cores drilled from long-lived massive corals such as massive *Porites* spp provide insight into how calcification has changed over the past centuries. Some studies[127,25], reported evidence of a slight increase in calcification over the decades prior to 1979 with calcification being highly correlated with average sea temperature (0.3 grams per $cm^2$ per year or 3.5% increase for each degree C of increase). Lough and Barnes[127] have proposed that the increase in calcification was probably due to the 0.25°C observed increase in sea temperature on the GBR during the same period and that, initially, some corals may increase their calcification rates as the oceans warm. There is, as yet, no observational evidence of decreases in coral calcification rates on reefs with the 0.1 drop in oceanic pH, though significant decreases have been observed in controlled laboratory experiments.

### *10.2.3.4 Adaptive capacity – ocean acidification*

Another group of authors[133] have used the observation of increased calcification over the past 100 years to conclude that the ocean acidification will be counteracted by the putative increase in calcification due to future warmer conditions. This assumption is invalid given that corals start to bleach at just 1°C above today's sea temperatures, and that the physiological literature also unambiguously shows that calcification increases up to the summer sea temperature maxima but then decreases rapidly thereafter[106]. Contrary to the predictions of the McNeil et al.[133] model, combinations of high sea temperatures and high $CO_2$ concentrations of future climate scenarios predict dramatic decreases in calcification rates. There would need to be an ever-increasing calcification rate (and a lack of negative influences from thermal stress) to enable the McNeil model to have any credibility. This and other problems with the methods and conclusions of McNeil et al.[133] are outlined and fully discussed in Kleypas et al.[106]. It seems that the ability of marine calcifying organisms such as corals to adapt to the unprecedented and rapid rates of changes in ocean chemistry, combined with additional stresses resulting from climate change (eg coral bleaching and more destructive tropical cyclones) will be limited.

### *10.2.3.5 Vulnerability and thresholds – ocean acidification*

Doubling atmospheric $CO_2$ above the ocean will cause the carbonate concentration to decrease to approximately 200 micromol per kg, with temperature having a small influence. A carbonate concentration of 200 micromol per kg is critical in that the calcification of corals and many other organisms declines effectively to zero at carbonate concentrations around this value. This impact is made even more significant because coral reefs are a balance between calcification and erosion and hence calcification needs to be well above zero to avoid a net erosion of coral reefs. There is overwhelming evidence that corals and the reefs they build will not be able to maintain themselves or grow if $CO_2$ concentrations rise above 500 parts per million[67,105,78,85,107]. This level of $CO_2$ is at the lower end of the range of greenhouse scenarios for the end of this century.

## 10.2.4 Sea level rise

### 10.2.4.1 Exposure – sea level

Coral reefs of the GBR have adjusted to sea levels that have prevailed for the last 6000 years (since current level reached at end of last Ice Age). Current sea levels, therefore, are one of the controlling factors in terms of coral distribution on the GBR in terms of water depth. Global sea level is rising due to the enhanced Greenhouse effect due to both thermal expansion (of the warmer ocean waters) and contributions from the melting of continental ice sheets and glaciers. Changes to sea level have been of the order of about 20 to 25 cm over the past century[155,36] and sea level is currently rising at 1 to 2 mm per year, an order of magnitude larger than the average rate over the previous several millennia[37]. Current projections[94] suggest a 0.1 to 0.9 metre rise of sea level by 2100. There is however, mounting concern that this rise in sea level may be higher as the Greenland Ice Sheet has been observed to be melting faster than expected. Loss of both the Greenland Ice Sheet and West Antarctic Ice Sheet would result in global sea levels that are more than 10 metres higher than present.

### 10.2.4.2 Sensitivity – sea level

Previous reviews have all concluded that these changes in sea level are relatively slow when compared to the rate at which corals are able to grow (up to 20 cm per year for branching corals[47]), and hence do not represent a major challenge for healthy coral populations. However, these maximum coral growth rates are rates of linear extension for individual coral branches, not the reef matrix itself. In addition, the emphasis is on healthy corals, which in turn may depend on the effect of rising sea temperature and ocean acidification, and on other stressors such as reduced water quality (eg turbidity and sedimentation).

### 10.2.4.3 Impacts – sea level

Due to the slowing effect of other factors on growth, there is the potential that coral populations might be left behind by rapid sea level rise. It is also important to keep in mind that these conclusions are dependent on having a slow rise in sea level. They would be invalidated in the longer term if, for example, the Greenland Ice sheet were to melt rapidly[152]. If this were so, then sea level rise would accelerate well above coral growth and would stabilise at 6 to 10 metres above current sea level. In this case, sea level rise would represent an extreme challenge for most marine habitats including coral reefs.

### 10.2.4.4 Adaptive capacity – sea level

A steady, relatively modest (eg 0.1 to 0.9 metres by 2100[94]) rise in sea level is unlikely to be a major problem for corals of the GBR as reef development has been constrained by current sea levels reached several thousand years ago. Corals with high growth rates may be able to keep up with projected sea-level rises. The potential for adapting to rising sea level depends, however, on healthy coral populations which is unlikely to be the case as continued ocean warming (increasing bleaching events) and ocean acidification (reducing calcification rates) compromise the viability of corals on the GBR.

### *10.2.4.5 Vulnerability and thresholds – sea level*

Corals of the GBR are probably less vulnerable to gradual and modest sea-level rise than to other climate change stressors. There is, however, mounting concern that the global rise in sea level is accelerating[36] and that the potential for catastrophic rises (of greater than 10 metres) may be triggered by loss of the Greenland Ice Sheet and, possibly the Western Antarctic Ice Sheet. Under such circumstances, extensive areas of coral communities on the GBR would be lost or compromised, as rapid changes in sea level would overwhelm the growth rates of corals pushing their communities into deeper, low-lit areas of the ocean. A massive contraction of coral distributions would almost certainly occur, in particular in coastal, turbid areas where photic zones are already compressed, until the climate stabilised once more.

## 10.2.5 Tropical storms, rainfall and river flood plumes

### *10.2.5.1 Exposure – storms and floods*

The number of severe cyclones (category 4 and 5 on the Saffir-Simpson scale) has nearly doubled over the past three decades in all ocean basins[193,59]. Using an index based on power dissipation during the life of each cyclone, Emanuel[59] showed that cyclone destructiveness has increased dramatically since 1970, correlated with the increase in tropical sea surface temperatures. The record number and intensity of storms in the Gulf of Mexico during 2005 (a record 28 storms of which 15 were classified as hurricanes with winds greater than 100 km per hour[b]) underscored the conclusions of both studies. If this trend in destructive cyclone activity continues to rise and interact with other climate change stressors, coral reefs will enter an era of disturbance of unprecedented dimensions.

### *10.2.5.2 Sensitivity – storms and floods*

Storm impacts are part of the natural disturbance regime on coral reefs, and in some areas may help maintain high species diversity by preventing monopolisation by competitively dominant species[42,44]. However, whereas intermediate disturbance regimes can favour ecosystem health, increased frequency of severe cyclones, such as those predicted for this century, may lead to physical damage and associated stressors beyond what reefs have previously experienced. One basic premise of the intermediate disturbance hypothesis[42] is that the disturbance frequency and/or severity are low enough to allow succession of the benthic community between events. Importantly, if the frequency or intensity of destructive storms increases beyond the reef's capacity for recovery between events, reef resilience will decline and may shift reefs into alternative, less desirable states[47,91].

Benthic communities reset to bare substrate and algae following severely destructive events will recover mainly through the slow process of colonisation by sexual recruits[43]. Milder cyclone impacts, on the other hand, often allow survival of some adult colonies that can recolonise bare patches by regrowth[44]. Communities of corals in coastal areas may be particularly sensitive to intensified cyclone regimes as associated secondary impacts such as terrestrial runoff and sediment resuspension will also escalate under intensified cyclone regimes (section 10.2.5.3). Interestingly, however, the shading and cooling effects of the often dense cloud cover[142] and enhanced surface convection associated

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[b] http://www.nhc.noaa.gov/2005atlan.shtml

with storms in regions beyond their primary impact area may alleviate risks of coral bleaching. For example, during late 2005, coral reefs in the southeastern Caribbean experienced the warmest sea surface temperatures and associated mass bleaching in history[c]. The passing of Hurricanes Katrina and Rita in the northern Caribbean in August to September, prior to substantial heating of the southern Caribbean, led to significantly reduced sea surface temperatures, solar irradiance, and thereby lowered bleaching risks (M Eakin pers comm). It is important to note, however, that such lowered bleaching risks on reefs in marginal impact areas are likely to be counteracted by the increased mortality risk from secondary stressors (eg runoff and sedimentation) in coastal areas subjected to major flooding events.

### 10.2.5.3 Impacts – storms and floods

The impacts of tropical storms extend well beyond the direct physical impact of the wind waves they generate. Secondary impacts following storms like Hurricane Andrew were more important than the physical impacts during the storm through changes in coastal runoff and reduced water quality in nearshore areas[156]. In coastal areas, tropical storms often lead to heavy rainfall and associated runoff on the scale of 100s of kilometres[62], whereas the destructive wind forces occur on a scale of 10s of kilometres. Major flooding events are runoff of freshwater and dissolved nutrients from coastal catchments is perhaps the biggest threat to corals in nearshore waters[45]. Freshwater plumes[34] and increased nutrient loading[45] may inundate reefs within 50 km of major river mouths. Although terrestrial discharges of suspended solids are deposited within a few kilometres of river mouths[65], resuspension of sediment due to wind waves[114] may reduce benthic light regimes dramatically[8], compromising coral energy budgets[7]. As these secondary impacts may persist for weeks following a cyclone[45], and may extend over a larger area than the physical impact area, they may cause far more damage to reefs than the structural impact *per se*. Given the recent tropical cyclone activity around Australia's coral reef coastlines, changes in storm intensity on Australian reefs are likely to be similar to those seen for other coral reef regions.

### 10.2.5.4 Adaptive capacity – storms and floods

Given that coral reefs have evolved under a stochastic, natural regime of storms, they undoubtedly have some capacity for adapting to locally intensified storm regimes. The more critical question is perhaps whether reefs can tolerate an intensified storm regime as well as impacts from multiple other stressors that are also predicted to intensify in the future. Perhaps most importantly, ocean acidification through increasing $CO_2$ levels (section 10.2.3) will severely reduce the capacity of corals to build skeletons[105] and potentially the ability of crustose coralline algae to consolidate the reef matrix (Diaz-Pulido et al chapter 7). Since increased erosion of calcium carbonate will increase the susceptibility of reefs to storm damage, the adaptive capacity of coral reefs to physical disturbances is likely to be rapidly exceeded. Future communities of corals will most likely lack high-diversity assemblages of branching *Acropora*, but may enter a phase of largely massive and/or semi-encrusting morphologies that have higher resistance to wave impacts.

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[c] http://coralreefwatch.noaa.gov/caribbean2005

### *10.2.5.5 Vulnerability and thresholds – storms and floods*

The vulnerability of coral reefs to increased storm intensity and flooding is highly interactive with the other side of the equilibrium within which coral communities sit. Major disturbances like category 5 storms can have a major impact on sections of coral reef yet are (currently) fairly infrequent events. Recovery from these natural events occurs over several decades and in past climate regimes has not led to any persistent decrease in coral community abundance. This equilibrium may shift as the frequency of catastrophic storms increase and recovery processes become increasingly compromised through ocean warming and acidification. This suggests that coral communities will become increasingly vulnerable as storm activity increases and recovery processes decline. Specific thresholds have not been identified. However, several modelling studies[96] have revealed that coral populations are highly sensitive to small changes in mortality or recruitment. This suggests that thresholds should be relatively easy to identify.

## 10.2.6 Changes in ocean circulation

### *10.2.6.1 Exposure – ocean circulation*

One of the ways the planet copes with differential heating patterns is to balance the energy budget by transporting heat from the tropics to the poles, which is achieved by both large-scale air and ocean currents. Ocean currents are driven by wind as well as fluxes of heat and freshwater, the latter referred to as thermohaline circulation. In our present climate, the sinking of cold water near Antarctica and in the northern Atlantic Ocean are drivers for a major conveyor system known as the Atlantic meridional overturning circulation[31]. Cold, dense water in these regions sinks to the bottom of the ocean from where dense flows spread toward the equator at great depth eventually rising to the surface and being returned to the poles. The Gulf Stream is the major surface current that closes the northern arm of the meridional overturning circulation and runs from the Caribbean, along the east coast of the USA to the Greenland-Norwegian Sea. It is this current that has the greatest sensitivity to climate change. At the edge of the GBR, the East Australian Current plays a major role in determining many of the environmental conditions discussed above that can influence coral condition. In addition to influencing basic water quality, the behaviour of these currents affect whether communities of corals are connected or not, and aspects of coastal weather (such as storms and doldrums) which in turn drive parameters that affect corals. Steinberg (chapter 3) discusses these large-scale variations.

### *10.2.6.2 Sensitivity – ocean circulation*

Since the drivers for the meridional overturning circulation are primarily the Artic and Antarctic ice sheets and to a lesser extent tropical heating, any change to the volume of ice at high latitudes, their melting rate, or heat input at low latitudes could affect the speed of this current. Melting of the Greenland and Antarctic ice sheets is happening at much faster rates than previously thought[152] and the resultant freshwater influx has the potential to slow down or even halt the North Atlantic meridional overturning circulation. The warm surface water of this conveyor forms the Gulf Stream, which normally provides northern Europe its relatively mild climate. A slowing down of the Gulf Stream is likely to abruptly and profoundly influence the climate of the northern USA and Europe with likely flow-on effects to the climate of the rest of the world. To a large extent, our understanding of the impact of climate change on ocean circulation is still rapidly evolving. It is clear, however, that many parts of the ecosystem are highly sensitive to changes in global temperature, and that coral reefs are highly sensitive to these changes.

### 10.2.6.3 Impacts – ocean circulation

Paleo-proxy records of the northern hemisphere show that a slowing down or halting of the North Atlantic meridional overturning circulation has occurred on a number of occasions in the past. The last major abrupt climate change occurred some 8200 years ago when two glacial lakes melted and drained into Hudson Bay, Canada[38,119]. This event is recorded in the $\delta^{18}O$ signature of Greenland ice cores and is estimated to have caused a 3 to 6°C decrease in northern European temperatures within a few years[4,161]. Bryden et al.[31] provide observational evidence that the oceanic density fields in the North Atlantic have changed considerably resulting in a weakening of the circulation of more than 30 percent between 1957 and 2004. A repeat breakdown of the circulation would have devastating effects on the socio-economic condition of countries bordering the eastern North Atlantic. The flow on effects to coral reef regions under such a scenario are uncertain, but could include enhanced warming and tropical storm activity in the Caribbean and global sea level rise[94], the consequences of which are discussed in sections 10.2.1.4, 10.2.4.3 and 10.2.5.3.

Although projecting the precise details of how ocean circulation will change is difficult, it is quite clear from current evidence that it is changing and that coral communities are highly sensitive to change. Currents determine aspects of the environment such as temperature and to an extent local weather. To see the effects of relatively minor changes in ocean currents on coral communities one has only to examine the large scale changes that have resulted during El Niño-Southern Oscillation (ENSO) disturbances to the Indo-Pacific in the 1982–1983[73] or 1997–1998 global ocean-atmosphere events[82]. The latter event involved changes (as was the 1982–1983 event) to ocean circulation and led to the loss of 16 percent of reef-building corals globally.

### 10.2.6.4 Adaptive capacity – ocean circulation

Forcing of ocean currents are subject to physical laws. As such there is little scope for 'adaptation' in the same sense as biological and human systems can adapt to changes. Ocean currents change in response to regional changes in heat fluxes, freshwater input, wind forcing and sea ice volume. These forcing factors interact in complex ways and themselves are a response to local and regional climate variation. For this reason anticipating the timing and dynamics of ocean currents is difficult to predict.

### 10.2.6.5 Vulnerability and thresholds – ocean circulation

Under present climate change models, the likelihood of a shutdown or slowdown in the North Atlantic meridional overturning circulation of sufficient magnitude to cause a cooling in the Europe is considered small (despite the large-scale changes it would bring). Meehl et al.[136] modelled the latent response of our climate system using two independent climate models and showed that even under a high-end A2 climate scenario, there was no cooling over northern Europe despite significant slowing of the meridional overturning circulation. This is principally because increases in greenhouse gas emissions and resultant warming overwhelmed any tendency to high-latitude cooling. The IPCC[94] notes that it is too early to say with confidence whether an irreversible collapse in the Atlantic

meridional overturning circulation is likely or not and at what threshold it might take place. However, none of the coupled models predict a complete shutdown of the current under any of the climate scenarios by 2100.

## 10.2.7 Linkages with other components

### *10.2.7.1 Constraints to adaptation*

Evidence for past adaptation of corals to distinct thermal regimes comes from the observation that populations from warmer locations can withstand higher temperatures compared to conspecific or congeneric populations that live in cooler water, and that those differences are maintained after laboratory acclimation[41,82,185,22,171,173]. These results suggest that variation in bleaching resistance of corals has a significant genetic component, which is a prerequisite for selection to lead to adaptive change. In other words, if all of the observed variation in bleaching resistance reflected phenotypic plasticity, corals would be unable to respond to selection for increased temperature resistance and hence would not adapt.

To predict the rate at which corals and their algal endosymbionts can potentially adapt given the most likely warming scenarios, it is useful to quantify the extent to which the observed variance in bleaching resistance is genetically determined using quantitative genetic approaches. This information is currently unavailable. A second important factor in estimating potential rates of adaptation of corals is the generation time, that is, the time period from birth to average age of reproduction. The longer the generation time, the slower the process of adaptation. Generation times in corals depend on their growth rates, as reproductive maturity is related to size[12]. The age at first reproduction is probably on the order of three to eight years, but because corals are iteroparous, the generation time should be a weighted average of the age of a maternal colony at which each of her offspring was produced[154]. Generation times for long-lived coral species that grow to large sizes are therefore expected to be significantly longer than three to eight years, as most offspring will be produced when the maternal colonies are large (ie at an older age) and after adult polyp fecundity has been reached[12].

*Symbiodinium* populations, on the other hand, are asexual in *hospite*, but population genetic studies show that sexual reproduction does occur although it may be infrequent[13,14,115,168]. *Symbiodinium* occurs at extremely large populations sizes (probably on the order of several billion cells per coral colony). Therefore, even in the absence of frequent sexual reproduction, infrequent somatic mutations may become relevant in such huge populations. Aided by clonal reproduction, selection may lead to the rapid dominance of cells that have undergone a mutation, which enhances thermal tolerance. This is very hypothetical, and experimental work should be directed to explore the likelihood that such evolutionary processes play a role in the evolution of *Symbiodinium*. Furthermore, it is unknown whether *Symbiodinium* with enhanced thermal tolerance will also increase the thermal tolerance of the holobiont.

In any of these discussions about the adaptation of populations of corals to climate change, it is important to note that climate change does not involve a step change but rather, is (and will continue to be) characterised by continuous change. This has important implications for the expectation of how populations of corals and other coral reef organisms may change. For example, if we were to stabilise global temperatures at 2°C above present day conditions, coral populations would see an initial decrease in population size as unfit genotypes are eliminated followed by the proliferation of fit genotypes at the new temperature. We might also expect the migration of thermally tolerant northern genotypes to migrate to southern locations on the reef over time (probably over decades), assuming that levels of gene flow are sufficient to accomplish this, and to flourish at these southern locations as conditions stabilised. The key part of this preceding statement is the stabilisation of climate, which is highly dependent on the rate of greenhouse gas emissions achieved over the next few decades. Stabilisation of climate becomes increasingly unlikely with anything less than aggressive reductions of greenhouse gas emissions (greater than 80% by 2050). Given that stabilisation is unlikely, notions of rapid adaptation changing the thermal thresholds of corals and their symbionts in whole communities are also unlikely. In the unlikely event that we could stop all greenhouse gas emissions today, we are still committed to significant climate change and disruption to habitats like coral reefs[136,195] before stabilisation is reached.

### *10.2.7.2 Interactions between stressors*

There are a large number of interactions between stressors, producing either muted or enhanced outcomes for corals and *Symbiodinium* as two or more factors coincide. These interactions have not been exhaustively pursued and should be the subject of future research work. Interactions between thermal stress and light have been explored at both physiological[101] and ecological[142] levels and via modelling[82]. As discussed above, the flow of water around corals also has an important effect on thermal and photic stress[144,145] and effects on the photosynthetic performance of zooxanthellae in hospite have also been documented[184]. Anthony et al.[9] explored the interaction between water quality, light and temperature, on coral bleaching and mortality and found that the complex interactions between these variables are largely explained by their effects on coral energetics. These interactions ultimately define environmental limits to growth[7] and are ultimately related to common variables within the energy budgets of corals that are attempting to undergo photosynthesis in the challenging conditions associated with life in coastal water.

Despite the fact that much is known about the interaction of some variables, we have only a hint of how factors such as thermal stress and acidification will interact under future oceanic conditions. As discussed above, the poorly constructed conclusions of McNeil et al.[133] stemmed from inaccurate assumptions about how coral calcification might fair in a warmer more acidic ocean. This highlights the importance with which we must address the questions of how different drivers will interact as the world changes. For example, the process of recovery of coral reefs following bleaching events is surprisingly poorly described despite the importance given to the concept of resilience. How fishing pressure affects reef recovery, or how poor water quality affects mortality following thermal stress need to be determined if we are to understand and better manage the impacts that appear almost certain as the global ocean warms and acidifies.

### *10.2.7.3 Coral disease*

Recognition that coral disease can be a major force in structuring coral communities has emerged only recently and has been based primarily on studies of Caribbean reefs in the past two decades[11,157]. The first record of a coral disease was in the early 1970s[10], but since then, more than 30 coral diseases have been described, the majority from the Caribbean (reviewed in Weil[194]). Disease is commonly defined as a deviance from the normal physiological functioning of an organism, but the distinction

between health and disease is not always clear-cut. The distinction is typically based on the extent of the dysfunction; mild dysfunctions of behaviour, growth and reproduction generally fall within the realm of relative health, whereas severe dysfunctions and mortality are classified as disease. Coral diseases may be either infectious or non-infectious (eg environmentally induced). Infectious diseases of corals are associated with a variety of pathogens, including bacteria, cyanobacteria, ciliate protists, and fungi, although causative agents (as verified using Koch's postulates) have been identified for only a few coral diseases (reviewed in Weil[194]). Surveys of coral disease reveal generally low (less than 5%) disease prevalence on reefs in the GBR[198]. Overall, seven disease types have been recorded: black band disease (BBD), skeletal eroding band (SEB), white syndrome (WS), brown band disease (BrBD), coral tumors, atramentous necrosis, and cyanobacteria syndromes (other than BBD), although current understanding of the majority of these is limited to field descriptions of lesions. All seven of these coral diseases are widespread throughout the GBR. For example, BBD occurs on more than 70 percent of reefs surveyed (n = 19) throughout the northern, central and southern sectors, although its prevalence is typically low (affecting about 0.1% of scleractinian corals)[153]. Black band disease has been recorded to infect at least 32 coral species in 10 families on the GBR, with branching pocilloporid and acroporid corals being important hosts[198]. Abundance of WS increased 20-fold in the 2001 and 2002 period, around the time of the most severe bleaching event so far recorded on the GBR, and increased further in 2002 and 2003[198] but has since declined to low levels in all regions (B Willis and C Page unpublished data). Detection of some of the more common and infectious Caribbean diseases (BBD and potentially some of the white diseases), in combination with discovery of diseases unique to the region (brown band disease[198]), suggest that coral diseases are common on Indo-Pacific reefs and may have a greater role in structuring Indo-Pacific coral communities than previously thought. Diseases are ubiquitous in all plant and animal populations, thus such contributions to the dynamics of coral populations are not unexpected. Increases in white syndrome abundance[198] and atramentous necrosis in the summer of 2001–2002[102] are the only disease outbreaks so far documented on the GBR. At present, diseases have had a comparatively low impact on GBR coral populations in comparison to those in the Caribbean. However, the impacts of coral disease in other reef areas highlight the potential for increased risk in the future, especially in a warming climate.

Increasing reports of diseases in many marine organisms globally in the past few decades are postulated to be linked to ocean warming[80,113,191,170]. Increasing sea water temperatures have the potential to increase not only host susceptibility to disease, but also virulence of the pathogens themselves[80,163]. It is difficult to separate the effects of ocean warming from concurrent increases in stressors such as nutrients, toxic chemicals and other pollutants, based solely on reports of disease[113]. However, a number of additional lines of evidence support a link between elevated temperatures and disease. For example, the role of high temperatures in summer outbreaks of bacterially induced bleaching in Mediterranean populations of the coral, *Oculina patagonica*, appears to be well established[180,95]. These outbreaks have been linked to increased expression of virulence genes by the bacterium, *Vibrio shiloi*, at higher temperatures (reviewed in Rosenberg and Ben-Haim[180]). Seasonal patterns in coral disease prevalence on the GBR[198] and spatial patterns in black band disease abundance in the Caribbean[111] support a link between elevated temperatures and the prevalence of a number of coral diseases (eg white syndrome), black band disease, skeletal eroding band and brown band disease on the GBR[198]. Recent analyses of the relationship between annual patterns in the abundance of white syndrome on the GBR and warm thermal anomalies also corroborate a link between elevated seawater temperatures and coral disease[170]. Speculation that warmer winter temperatures will favour pathogen populations and therefore not provide a winter reprieve from pathogen load associated with current mean winter minima[81] represents another potential way in which climate change may affect disease dynamics in GBR coral populations.

It is noteworthy that, in addition to temperature and environmental stressors, biological factors may also affect disease incidence, thus predicting the vulnerability of coral populations to disease as a consequence of climate change is complex. Host density is known to affect pathogen transmission[5] therefore reduced cover of dominant coral species may lower the spread of disease once low host density thresholds are reached. It is also possible that pathogens, which are currently positively affected by summer temperatures, will be negatively affected at higher sea water temperatures associated with climate change. Furthermore, there may be reduced coral disease under climate change scenarios as elevated sea water temperatures negatively affected some pathogens[112]. Evidence that an acroporid tissue loss syndrome decreases in abundance during the summer months at Heron Island[162,3] supports this possibility. These studies have documented programmed cell death (apoptosis) as the mechanism underlying tissue loss, although the trigger (eg environmental stress or microbial pathogens) for cell death is unknown. The greater disease abundance in winter may relate to dwindling energy resources (perhaps due to thermal stress in the preceding summer) prior to entering the colder, darker months. In summary, the impact of ocean warming will depend on relative thermal optima of coral hosts and pathogens. However, the potential for rapid spread of pathogens throughout marine populations, as demonstrated by the rapid spread of herpes virus throughout Australian pilchard populations and of morbillivirus throughout seal and dolphin populations[130], highlights the need for greater understanding of mechanisms of coral pathogen transmission and virulence, as well as mechanisms of disease resistance of corals, to better evaluate the vulnerability of corals to disease as a consequence of climate change.

#### 10.2.7.4 Threats to resilience

This chapter is devoted to the impacts of climate change on reef-building corals. It is important to note, however, that impacts on corals are likely to reverberate throughout the GBR ecosystem. Corals are responsible for the physical and ecological foundations that underpin reefs, making the fate of coral communities a critical determinant of ecosystem resilience. The many chapters in this book provide important insights into how impacts to coral communities from climate change will affect particular species or habitats. Emerging as important to understanding how impacts on corals might affect resilience more generally, is an awareness of the dependency between corals and other habitat components.

Corals support tens if not hundreds of thousands of other organisms. Many of these are totally dependent on corals for food, shelter and reproduction. Many others rely only partly on corals, while nearly every organism has some sort of indirect dependency on the goods and services provided by corals. Where direct and strong dependencies occur, changes in coral cover or composition can have obvious and immediate impacts on other species. Coral obligates like the orange-spotted filefish (*Oxymonacanthus longirostris*), for example, rapidly disappeared from Okinawan reefs after the 1998 bleaching event[109]. In contrast, less direct or facultative relationships can result in complicated, delayed or minor responses to changes in coral communities. In the Seychelles, for example, Spalding and Jarvis[174] found that the overall structure of fish communities had changed very little despite massive decreases (3 to 20 fold) in living coral cover after the 1997–1998 bleaching event. This effect

is amplified further up the trophic pyramid, as exemplified by the difficulty in detecting impacts on reef-based fisheries after major coral mortality events caused by bleaching[35]. Competitive interactions involving corals are also important to the composition and dynamics of coral reefs. The ability of corals to dominate available hard substrate to the exclusion of algae, for example, is fundamental to the long-term resilience of the ecosystem[131].

These illustrations highlight the complex web of relationships that centres on corals. Changes in the abundance or composition of coral communities will necessarily have impacts on other parts of the ecosystem, with the potential to severely undermine resilience. This emphasises the importance of measures that take into account the complex responses that are likely from inter-dependent ecosystems such as the GBR, rather than a focus on any one species, group or habitat. In the context of climate change, more than any other issue, understanding the connections between different parts of the ecosystem, and the role of species or groups in ecosystem resilience is critically important when formulating management responses. In particular, taking a resilience-based approach to the management of tropical marine ecosystems (McCook et al. chapter 4, Marshall and Johnson chapter 24) is critical to address the issue of climate change, where impacts are certain to occur, but their scale, intensity and frequency is largely unknown.

## 10.3 Summary and recommendations

### 10.3.1 Major vulnerabilities to climate change

The vulnerability of coral and the reefs they build to climate change was bought into sharp focus after 1998, when an estimated 16 percent of the world's coral communities died. Analysing the literature since that time reveals that rapidly rising sea temperatures and increasing levels of acidity in the ocean remain the major threat to coral reefs. Successive studies of the potential impacts of thermal stress on coral reefs[82,48,49] have supported the notion that coral dominated reefs are likely to largely disappear with a 2°C rise in sea temperature over the next 100 years. This, coupled with the additional vulnerability of coral reefs to high levels of acidification once the atmosphere reaches 500 parts per million[105,78,107], suggests that coral dominated reefs will be rare or non-existent in the near future. In this regard, we conclude that communities of Australian corals are extremely vulnerable to the effects of ocean warming and ocean acidification. While new assemblages will certainly form in the absence of coral-dominated reefs, the diversity and structure of these communities as well as the types of fishing and tourist industries they might support are completely unknown.

Changes to other factors such as storm intensity, water quality and light intensity will have a lower, yet significant, impact on coral reefs. Although coral reefs are less vulnerable to these particular factors, and hence they are likely to interact with climate change and ocean acidification in some important ways. Increased storm activity, for example, may reduce the effects of climate change locally by mixing the water column and cooling the overlying waters. Stronger storms, however, will accelerate the breakage of increasingly fragile coral skeletons caused by ocean acidification and will cause larger coral mortality events in coastal areas due to more intense flooding. Other factors such as increasing sunlight days as the Australian coastal areas undergo drying will exacerbate the effects of warming. Although a full understanding of the many interactions with secondary variables has not been achieved, their role in the vulnerability of coral reefs is likely to grow.

### 10.3.2 Vulnerability and thresholds (extinction risk and irreversibility)

As outlined above, 500 parts per million is the highest $CO_2$ concentration under which any semblances to the communities of corals we have today can survive. It is also the only scenario in which the climate will eventually stabilise. Above this point (500 parts per million), coral reefs will also change irreversibly and be lost for many thousands of years. To contemplate any higher $CO_2$ is untenable given the huge likelihood of such catastrophic events as runaway greenhouse effects and the flooding of the planet as the Greenland and Western Antarctic Ice Sheets melt. Even though 500 parts per million is seen as an ambitious greenhouse target, effects on ocean temperature and acidity will mean that coral calcification will decrease to 40 percent of today's value and major (1998 level) bleaching events will occur every 2 to 4 years[82,48,49]. Under these conditions, Australian reefs will have the following characteristics:

- Major increase in the frequency and intensity of coral bleaching, mortality events and recruitment failure with increased incidences and outbreaks of coral disease.
- Coral dominated reefs will contract to less that 20 percent of today's distribution and corals will be rare on most coral reefs. Benthic microalgae, macroalgae and cyanobacteria communities will dominate these reefs although it is uncertain which species or taxa will dominate.
- Reef carbonate frameworks are likely to slowly disintegrate under vastly reduced calcification (due to elevated temperatures and decreasing pH) and the possible acceleration of bioerosion. Reefs will have less structure and hence reduced habitat complexity and holding capacity for reef organisms. It is not known how long these processes will take to have an effect on coral reefs.
- Reduced coral communities and reef structure will lead to a major reduction in reef biodiversity with some coral-dependent species going extinct.
- At longer time frames, negative reef maintenance and growth will mean that sections of the Australian coastline that are currently protected by reef structures like the GBR will gradually become more exposed to ocean wave stress. This may eventually have ramifications for the current distribution of coastal seagrass and mangrove communities.
- Intensified cyclone regime will increase physical impacts on coral communities and will accelerate the shift from high-diversity communities to assemblages dominated by few resistant massive/encrusting species. Reduced vitality of corals will mean that recovery will be compromised; further accelerating the shift of reefs away from coral dominated reefs.
- The increased intensity of flood events along with prolonged drought along east Australia will lead to periods of reduced water quality and flooding (with associated sediment, nutrients, and freshwater impacts) that will affect reefs further offshore.

### 10.3.3 Potential management responses

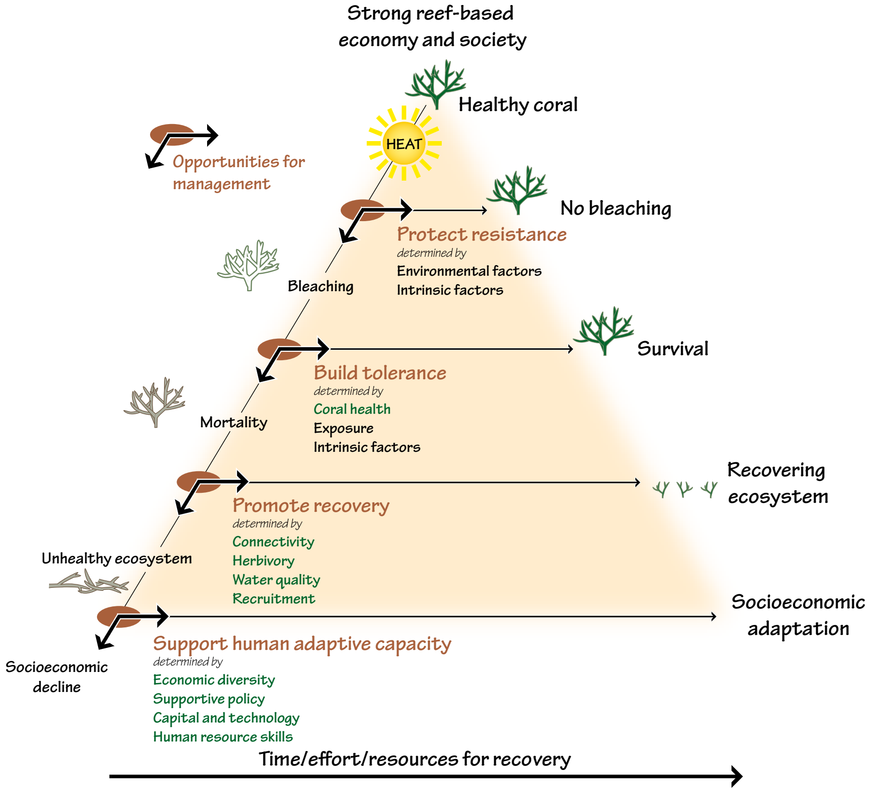
The most serious threats to corals in the context of climate change are coral bleaching caused by warming sea temperatures, and decreased calcification due to ocean acidification. Neither water temperature nor ocean chemistry is amenable to mitigation at the scale of local reef management. However, there is a variety of local factors that are can influence the susceptibility of corals to global stressors. An understanding of the process of coral bleaching, and the factors that influence outcomes

at various steps along the causal pathway, provides the basis for scientifically-based management strategies that aim to reduce the impacts of climate change on corals[149,135].

A similar analysis may be possible for ocean acidification in the future, once more is known about the interactions between aragonite saturation state and other (more local) factors that influence calcification in corals. Possible management strategies at the local scale could be measures to (1) increase pH to shift the aragonite saturation state, or (2) reduce wave regimes locally to protect patches of more susceptible morphologies from breakage. This could probably only be achieved in enclosed reef areas (eg micro atolls). However, it is unlikely that such attempts would be cost effective as a conservation strategy or as a rescue operation for tour operators.

Three conditions determine the outcome of stressful temperatures on corals: resistance, tolerance and reef recovery. Each of these offers a potential focus for management action aimed at reducing the impacts of coral bleaching (Figure 10.1). Damage to a coral community might be reduced if managers can influence or somehow enhance the effects of factors that determine the ability of corals to maintain their symbiotic dinoflagellates even when exposed to high temperatures (protecting resistance). Experiments to test the effectiveness of shading corals during periods of hot,

***Figure 10.1*** *The coral bleaching process, showing opportunities for management action to reduce the impacts of stressful sea temperatures on coral communities (from Marshall and Schuttenberg 2006)*



still conditions are an example of efforts to protect resistance at a very limited spatial scale. Managers may also be able to build the ability of corals to tolerate bleaching. In particular, recent research has shown that the lipid content of corals affects their ability to endure bleaching[9], suggesting that management strategies aimed at maintaining coral health (such as improving water quality) may play an important role in reducing the severity of coral bleaching. The part of the bleaching process most amenable to management action is the potential for coral communities to rapidly recover following coral mortality. Healthy habitats are better able to provide the conditions required for recruitment, survival and growth of new corals after bleaching has killed established colonies. In particular, good water quality, an abundant and diverse community of herbivores, and high coral cover are key aspects of ecosystem quality that should be priorities for reef management that aims to minimise the impacts of climate change on coral communities[199].

Although there are management actions that can reduce the impacts of coral bleaching, ultimately the fate of coral reefs will be determined by a combination of the rate of climate change, and their resilience to these changes. This suggests that immediate steps must be taken to reduce the sources of emissions that are driving climate change. In addition, the interaction of climate change impacts with secondary factors (eg water quality and fishing pressure) suggests some important strategies that need to be undertaken as climate change continues. These would build on the significant steps that have already been taken to improve the resilience of the GBR ecosystem, such as increasing the area of no-take zones from 5 to 33 percent, and developing a Reef Water Quality Protection Plan. Together, these measures have been hailed as being of international conservation significance. However, climate change poses additional and new challenges to tropical marine ecosystems, requiring further management efforts. Based on what is currently known about the risks from climate change, we offer the following recommendations:

- To minimise the risk of major degradation of coral reefs, global emissions need to be reduced so that atmospheric concentrations of $CO_2$ stabilise at levels no higher than 500 parts per million.
- Management effectiveness will be benefit from a thorough understanding of regional differences in vulnerability across all stresses. Hence, a more detailed understanding of the basis of tolerance in organisms like corals and their symbionts as well as a detailed ‘vulnerability map’ for the GBR can contribute substantially to resilience-building efforts.
- Reef resilience will also be improved through effective management of river catchments (ie reduced erosion potential of particulates, nutrients and toxicants) so as to improve coastal water quality and prepare for the impacts of more intense storms on an increasingly drought ridden coastline.
- Continued protection of healthy herbivore populations will help maintain and promote coral recruitment into disturbed areas.
- Explore the pros and cons of artificial structures to maintain reef species in areas where corals have been removed and the reef framework has disintegrated, or as stepping-stones between source and sink reefs in areas of low connectivity.
- Efforts to explore the effectiveness and costs of technologies to reduce climate impacts (shade structures, restoration technologies) should be facilitated for small areas of high natural or industry (tourism) value.

### 10.3.1 Further research

Our analysis reveals numerous gaps in our understanding of how corals and their dinoflagellate symbionts will survive under rapid climate warming and ocean acidification. Although we are rapidly improving our understanding of how corals are affected by thermal stress and acidification, we need to improve our understanding of how these conditions affect other important reef species, especially those that are important reef calcifying organisms (eg calcareous red algae). It is imperative that we pursue an understanding of the molecular basis for stress tolerance in corals and their symbionts. As the tools of the later exist, engaging in a national research program to achieve this must be a priority. We need to also expand our understanding of how climate change and ocean acidification will interact, both together and with other climate related factors (eg storm intensity). At higher levels of organisation, we need to improve our understanding of the consequences of the loss of corals as major community members on Australian reefs. In this regard, a regional 'vulnerability map' would be a valuable tool for understanding the interplay between local and global stresses in complex ecosystems like the GBR. Assessments are also needed of how reef biodiversity is tied to, and affected by, the abundance of reef-building corals. Equally, we need to know how projected changes in benthic community structure will affect commercial fish stocks, and to explore ways that we might ameliorate these changes (eg artificial reef structures). Other industries such as marine tourism (one of Australia's largest industries and export earners) will be affected by severely degraded coral reefs. Some analyses of this problem have been undertaken. Projections of vulnerability of these industries and reef usages, however, need to be coupled with socio-economic studies that examine strategies to reduce the impact and spread the risk to these industries of major changes in the appeal of coral reefs to visitors. Lastly, we need to understand better how changes in the health of tropical marine ecosystems in Australia's backyard (southeast Asia and the western Pacific) will affect the status of societies that depend on coral reefs for food and resources. In this respect, Australia needs to understand and be ready for potential impacts on the social and economic well-being of millions of people who depend for subsistence on the coral reefs in neighbouring countries.

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## Part II: Species and species groups

# Chapter 11

## Vulnerability of benthic invertebrates of the Great Barrier Reef to climate change

Pat Hutchings, Shane Ahyong, Maria Byrne,
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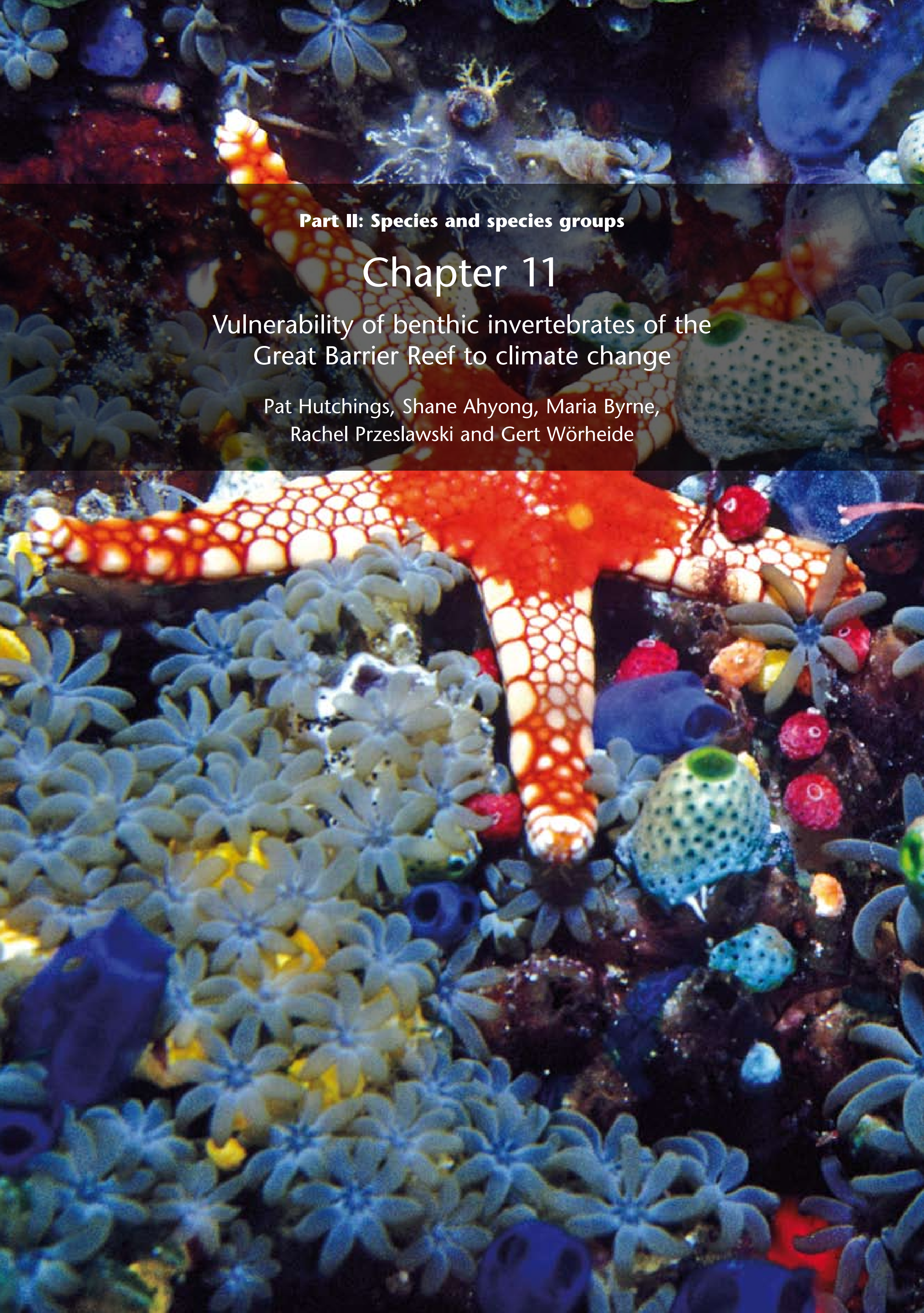


## 11.1 Introduction

This chapter deals with benthic invertebrates inhabiting the extensive inter-reef soft bottom habitats and those occurring on the reef, excluding corals. For the remainder of the chapter, the term 'benthic invertebrate' refers to all invertebrates excluding corals. An assessment of the impacts of climate change on non-coral benthic invertebrates poses particular challenges: i) benthic invertebrates include an extraordinary diversity of marine organisms, including many microscopic, infaunal, boring or ephemeral species that can be difficult to sample and are poorly known taxonomically; ii) benthic invertebrates employ a diversity of reproductive strategies, broadly including planktotrophy (development through feeding larvae), lecithotrophy (development through non-feeding larvae) and direct development (release of post-metamorphic juveniles), as well as asexual reproduction, making broad generalisations of dispersal capabilities difficult; iii) factors determining species distributions are poorly known for most species; iv) benthic invertebrates exhibit a tremendous variety of lifestyles and forms, including colonial, sedentary and errant species; v) many species include either a pelagic larval or adult stage, so effects of climate change may vary during their lives (see McKinnon et al. chapter 6 for comments on planktonic forms); and, vi) research on the biogeography of benthic invertebrates on the Great Barrier Reef (GBR) is strongly biased towards commercial or destructive species.

Owing to the general lack of data on marine invertebrates on the GBR, much of our comparative information will be taken from examples based on other coral reef areas. In some cases, this will include studies from temperate areas, information from the fossil record, and data from closely related species that occur elsewhere.

This chapter will focus on representatives of the most conspicuous groups: sponges, echinoderms, molluscs and crustaceans, with comments on other groups wherever possible.

No attempt has been made to include meiofauna in this review, which, while being abundant and diverse on the GBR, have been poorly studied. Many of the generalisations made about the macrofauna, however, would also be applicable to this component of the fauna. While mention is made of intertidal habitats, this will be more fully covered in the coastal and estuarine chapter (Sheaves et al. chapter 19). Similarly, species living in estuarine habitats will be covered in more detail in the mangrove chapter (Lovelock and Ellison, Chapter 9).

### 11.1.1 Benthic invertebrates of the GBR

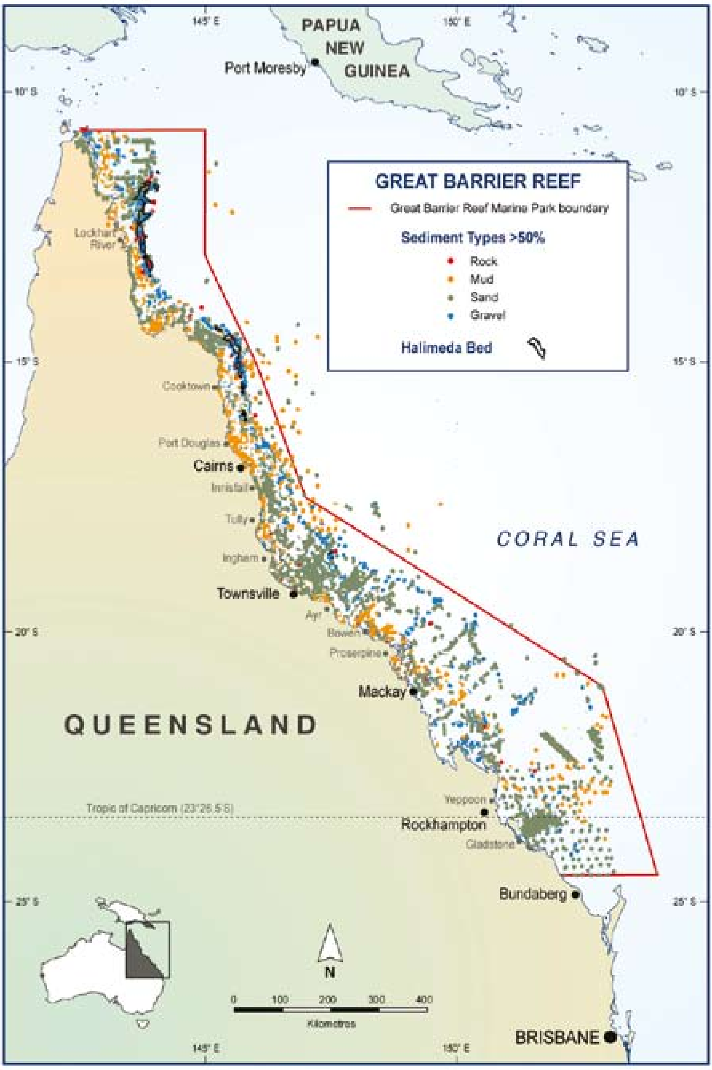
Benthic invertebrates are diverse and abundant both on reefs and in inter-reef areas. Most, if not all, marine phyla are represented[257], ranging in size from microscopic to macroscopic (up to 1.5 metres in length for *Tridacna gigas*). Our knowledge of the fauna is patchy and biased towards larger animals, especially those living on coral substrate, and those associated with commercial harvesting, shell collecting, or aquaculture[211]. Ponder et al.[211] summarise what is known about all the macro invertebrates found on the GBR, and Hutchings et al.[144] provide a synopsis of the benthic invertebrate diversity.

#### *11.1.1.1 Soft-bottom communities*

The GBR includes soft-bottom communities that extend from the coast to beyond the outer barrier reefs, from shallow intertidal zones to depths of 200 metres. Most of these communities occur within the Great Barrier Reef lagoon. Some areas are vegetated; the boundaries of some seagrass beds are well

defined (Waycott et al. chapter 8) and extensive meadows of *Halimeda* occur in deep water (50 to 96 metres) along much of the GBR[73]. Sediments range from fine mud at the mouth of rivers to calcareous sands[151,251] (Figure 11.1) that largely determine species composition[141]. Sediment type is often used as a surrogate for biodiversity in defining the bioregions in inter-reef habitats of the GBR[a,68], though latitudinal variation may be masked by the distribution and availability of suitable sediments.

***Figure 11.1*** *Distribution of sediments in the GBR*



Prepared using data from the GBRMPA and Australian Institute of Marine Science.

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a For further information, see www.gbrmpa.gov.au/corp_site/key_issues/conservation/rep_areas

The Great Barrier Reef Seabed Biodiversity Project coordinated by the Australian Institute of Marine Science is attempting to map and document sessile epibenthic fauna[b]. This report, due for completion in mid 2007, records many new species and new occurrences of species across the GBR (P Doherty pers comm). Nevertheless, this extensive spatial survey has collected only the larger epibenthic fauna and some of the larger infaunal organisms, because dredges and videos were employed rather than grabs. Complete documentation of GBR biodiversity will take years, if not decades, to complete. No comprehensive infaunal survey has been undertaken. Although Birtles and Arnold[24,25] did complete several infaunal cross-shelf transects in the 1970s and 1980s, sorting of the samples has not been completed. Elsewhere, infaunal lagoon sediments have been found to have very high species richness and diversity[5,157,92].

### *11.1.1.2 Coral reef communities*

More than 2900 coral reefs are present throughout the GBR region, varying greatly in size and position, from shallow inshore waters to the outer barrier reef. This includes fringing reefs around more than 900 islands, shallow and deep isolated reefs, and those forming extensive reef ecosystems[133,134].

While the corals of the GBR are well documented and exhibit considerable across-shelf and latitudinal variation[280], patterns for associated fauna are far less well known. Benthic invertebrates occur both on the surface of the reef, and deep within the coral substrate as borers (eg molluscs, polychaetes, sponges) or as cryptofauna (eg molluscs, polychaetes, bryozoans, brachiopods) living in burrows or crevices sometimes created by the borers[138,227,172]. Knowledge of the diversity of borers and cryptofauna of coral substrates is limited to a few localised studies[103,138]. Hutchings[137] and Peyrot-Clausade et al.[208] showed that the composition of the boring community is largely determined by substrate type (ie coral species) and the time since coral death, with the community changing as the substrate is bioeroded[202].

## 11.1.2 Current understanding of bioregionalisation

### *11.1.2.1 Sponges*

Major trends from biodiversity analyses of Australian tropical fauna at smaller 'intra-regional' spatial scales indicate that sponges frequently form spatially heterogeneous assemblages with patchy distributions[129], sometimes with as little as 15 percent similarity in species composition between geographically adjacent reef sites[126]. Several environmental variables are known to contribute to community heterogeneity: light, depth, substrate quality and nature, availability of specialised niches, water quality and flow regimes, food particle size availability, and larval recruitment and survival[288,127,229]. At larger landscape scales (ie scale diversity, definition from Hooper et al.[132]), latitudinal gradients of species richness are absent, moving from eastern temperate to tropical coastal and shelf faunas[131,132]. However, significant differences in species composition are evident between the major Australian marine coastal and shelf bioregions, the Coral Sea and sub-Antarctic territories[130]. Those differences might be the result of glacial sea-level changes that have impacted current systems and the resulting connectivity among regions.

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[b] www.reef.crc.org.au/resprogram/programC/seabed/index.htm

One of the three biodiversity ‘hot spots’ around tropical Australia, each containing more than 600 species of sponges, is restricted to the mid- and outer reefs on the GBR, including the Coral Sea Reefs and the Marion Plateau[132]. Lizard Island and the Capricorn Bunker Group in the southern GBR (more than 250 species each) were found to have exceptionally rich faunas.

Although clear bioregionalisation of sponge distributions was not evident, between 5 and 15 percent of regional faunas (New Caledonian fauna[130], Sahul Shelf fauna[127]) appeared to have wide Indo–Pacific ranges. More recently, however, molecular evidence disputed the existence of these so-called widely distributed species (eg *Astrosclera willeyana*[296], *Chondrilla* spp.[273]), suggesting that they may instead consist of several cryptic sibling species, each with high genetic diversity that is not clearly manifested morphologically. However, determining acceptable, definable or practical spatial scales for these cryptic species boundaries still remains unclear.

### *11.1.2.2 Echinoderms*

Echinoderms are a conspicuous and diverse component of the invertebrate fauna of the GBR[57,76,55,99,235,22,39]. The 630 species of echinoderms recorded from the GBR are divided as follows: sea stars (Asteroidea), 137 species; brittle stars (Ophiuroidea), 166 species; sea urchins (Echinoidea), 110 species; sea cucumbers (Holothuroidea), 127 species; and feather stars (Crinoidea), 90 species. Although a detailed bioregionalisation survey has not been carried out on echinoderms of the GBR, the recent Great Barrier Reef Seabed Biodiversity Project is likely to significantly expand our knowledge of the group. For the most part, echinoderms from tropical Australia are non-endemics with a broad distribution in the Indo–Pacific Ocean[76,56,71,236,235,109,237]. Some currently recognised echinoderm species may prove to be complexes of species, some of which may be discerned by life history traits and subtle morphological differences[62,196]. For example, several sea star species in the genera *Cryptasterina* and *Aquilonastra* have been shown to each comprise a species complex[62,197], and some of these species could be endemic to the GBR[37]. The *Cryptasterina* group includes both free-spawning species with a planktonic larva and viviparous brooders that give rise to crawl-away juveniles[62,35]. Molecular analyses have been key to discovery of this previously undetected species diversity. Similarly, several studies of sea stars indicate genetic differences within populations on either side of the Indo–West Pacific break[292,18,293]. Some of these genetic differences in the crown-of-thorns starfish (*Acanthaster planci*) and the cobalt-blue starfish (*Linckia laevigata*) may have been influenced by recent past (Pleistocene) changes in climate and sea level[18]. Both of these are free spawners with a dispersive larva[21,292]. This indicates strong potential for modification of the genetic structure of marine invertebrate populations as a result of climate change.

Sea cucumbers and brittle stars are the most abundant echinoderms in most parts of the GBR, though species of *Echinometra* and feather stars, living in the open, are perhaps more conspicuous in subtidal areas[7,25,22,78,39]. Although diverse, sea stars are not abundant, with the exception of spectacular outbreaks of *Acanthaster planci* (crown-of-thorns starfish). Sea urchins, too, are generally not abundant on the GBR compared with other areas[13,221], although species of *Echinometra* and *Diadema* can be locally abundant.

Sea cucumbers form a diverse and conspicuous assemblage of species throughout the GBR. They live in a variety of habitats, from exposed reefs (eg *Actinopyga mauritiana*) to intertidal and deep lagoons (eg *Holothuria, Actinopyga, Stichopus* species)[110,109,274,39]. Sea cucumber genera include commercial species that comprise the bêche-de-mer fishery. A recent genetic study of the commercial sea cucumber (Holothuroidea) known as the black teat fish, *Holothuria nobilis*, revealed that the fishery was composed of at least two species separated at the Indo–West Pacific break: *H. nobilis* from the Indian Ocean and *H. whitmaei* from the Pacific[277]. The taxonomy of several other commercially important sea cucumber species and species complexes on the GBR is currently being investigated[36].

The species richness of brittle stars on the GBR is impressive, with species in the families Ophiocomidae, Ophiotrichidae and Ophiodermatidae being well represented. Brittle stars are often common under slabs of coral rubble and in crevices shoreward of live coral habitats[252,40].

The echinoderm fauna of the northern GBR is more diverse than the fauna along the southern margin in the Capricorn Bunker group (Byrne, unpublished data). For example, brittle stars are particularly diverse in the northern GBR where they utilise rubble and boulder habitat and can be very abundant in shallow water and intertidal areas[39]. While this habitat exists elsewhere, such as One Tree Reef on the southern GBR, a similar diversity and abundance of tropical brittle stars is not evident (Byrne, unpublished data). The reason is not known, but may be related to larval supply. In contrast, holothuroids are prevalent throughout the GBR and are abundant and diverse in the southern GBR[112,113, 114,39].

### *11.1.2.3 Molluscs*

Molluscs pose a unique challenge in regard to examination of their distribution patterns on the GBR. Gosliner et al.[102] estimated that molluscs encompassed 60 percent of all marine invertebrate species in the Indo–West Pacific, and the phylum is one of the largest and most diverse in the marine environment. Thus, Mollusca are rarely examined in their entirety in biogeographical studies. Rather, a particular class or smaller taxonomic or ecological group is typically surveyed. Moreover, molluscan surveys on tropical reefs are usually biased towards macromolluscs, do not account for parasitic or commensal species, and do not adequately consider spatial heterogeneity, thus greatly underestimating overall molluscan diversity[27]. There is also a much larger emphasis on shelled species compared to sacoglossans, nudibranchs and other unshelled molluscs. Thirty percent of the estimated 3400 Indo–West Pacific opisthobranch species are probably undescribed[101]. Intensive surveys in New Caledonia revealed 2738 species of molluscs, an order of magnitude larger than previously reported for this region[27] and likely similar to GBR molluscan diversity. Single specimens represented 20 percent of these species, and 28.5 percent of species were represented only by empty shells, suggesting that the current number of molluscan species recorded in the tropical Indo–West Pacific considerably underestimates actual diversity[27]. This same survey identified molluscs ranging in size from 0.4 to 450 mm, with most species (33.5%) having an adult size smaller than 4.1 mm. In contrast, 'seashell' species (larger than 41 mm) accounted for only eight percent of total species[27], but research and surveys often focus on these larger species (eg Catterall et al.[46]), particularly those of commercial importance.

The large area and discontinuous habitat of the GBR makes spatial heterogeneity particularly important to quantifying molluscan diversity. Molluscan diversity and abundance in a given community are influenced by many abiotic factors. Substrate is one of the most important factors to influence molluscan assemblages[11,302], with great variation among hard- and soft-bottom assemblages. Small, herbivorous gastropods with low species diversity often dominate in seagrass beds[173], while larger predatory macromolluscs are more common on hard substrates, particularly coral reefs. A survey of a drowned reef off the Venezuelan coast revealed that only 21 percent of macromollusc species

were found in both soft- and hard-bottom areas[33]. Great variation in molluscan assemblages also exists within hard- and soft-bottom communities. On hard substrates, coral-associated molluscs are prevalent on coral reefs, and encrusting and crevice-dwelling bivalves dominate non-coral substrates[302]. The quality of hard substrates seems to particularly influence the abundance of predatory gastropods, with more neogastropods on hard substrates with refuges than on flat hard surfaces[161]. Both infaunal bivalves and gastropods are found in sandy substrates, and these assemblages may directly correlate with grain size. Molluscan assemblages in soft sediments show continuous variation related to environmental gradients[69].

Similar to other phyla (eg echinoderms, crustaceans), molluscs on the GBR include a comparatively large proportion of species with a broad Indo–West Pacific range. In a study of molluscs on Elizabeth and Middleton reefs immediately south of the GBR, 89 percent of molluscan species sampled occurred throughout the Indo–West Pacific and only 3.1 percent of these species were endemic[169]. Despite their low richness, endemic species may be the most abundant on some reefs[169]. Surveys of benthic invertebrates indicate that volutes have the highest degree of endemism, and overall endemism occurs most frequently on the GBR with shared components between New South Wales and southern Queensland[171].

Some species with a high level of genetic differentiation between archipelagos elsewhere in the Indo–West Pacific show little genetic variation on the GBR, such as the turbinid *Astralium*[183]. Similarly, the giant clam *Tridacna maxima* shows significant genetic variation between archipelagos in French Polynesia, but even with its high dispersal capabilities[166], shows little differentiation on the GBR[19]. Within the GBR, genetic diversity may show latitudinal gradients. Two tropical trochids with similar lecithotrophic life histories (including the commercially harvested *Trochus niloticus*) show increasing genetic differentiation from northern to southern GBR populations[26]. Reasons for these patterns remain unknown but suggest that distance alone does not control marine speciation[183].

### 11.1.2.4 Crustaceans

Crustaceans are speciose and abundant throughout the GBR with around 1300 species so far recorded from the area. The most conspicuous are the comparatively large decapods (crabs, shrimps and lobsters) and stomatopods (mantis shrimps), and other small-bodied but speciose groups such as peracarids, ostracods and copepods. Nevertheless, little information is presently available on the bioregionalisation of Crustacea on the GBR. Many of the commercial decapods in Queensland waters exhibit heterogeneous latitudinal and longitudinal distributions. For instance, northern, central and southern prawn fisheries are dominated by Endeavour (*Metapenaeus* spp.) and tiger prawns (several species of *Penaeus*), banana (*Fenneropenaeus merguiensis*) and red-spot king prawns (*Melicertus longistylus*), and bay (*Metapenaeus* spp.) and eastern king prawns (*Melicertus plebejus*), respectively[291]. The red-spot king prawn is a largely reef or inter-reef species favouring calcareous sediments, whereas banana and giant tiger prawns favour muddy inshore turbid waters on muddy substrates. Though juveniles of many species of commercial prawns use the same nursery habitats (namely coastal seagrass), adults have different substrate preferences[60,260,106]. Similarly, commercial crabs and crayfish are not uniformly distributed throughout eastern Queensland. The blue swimming crab (*Portunus pelagicus*), though ranging along the entire Queensland coast including inter-reef areas, appears in greatest numbers in southern coastal waters. The mud crab (*Scylla serrata*), also ranging widely in

Great Barrier Reef waters, is most common coastally where its favoured mangrove habitat is principally located. Similarly, tropical spiny lobsters (eg *Panulirus ornatus* and *P. bispinosus*) are most prevalent in the northern GBR, although they range further south into New South Wales[70,63].

Assemblages of coral-associated crustacean cryptofauna exhibit highest abundance and species richness on back-reef sites on mid-shelf reefs[214,215]. Whereas copepods dominate mid-shelf cryptofaunal assemblages, the proportions of ostracods and peracarids are significantly higher on inner-shelf reefs, despite lower overall richness. Factors that might account for the observed patterns are scale-dependent, with primary production variation at the cross-shelf scale and microhabitat features at the replicate level. Similarly, the highest diversity and density of pelagic copepods on an inter-reef transect of the central GBR occurs in mid-shelf waters[289].

Similar patterns have also been observed for Indonesian coral-dwelling Stomatopoda, with highest species richness on mid-shelf reefs[77]. However, composition of inshore, mid-shelf and outer-reef stomatopod 'communities' was significantly different. Distribution patterns of stomatopod species in the lagoons of New Caledonia and the Chesterfield Islands indicate patchy and discontinuous distributions that are highly correlated to environmental variables such as sediment type, terrigenous input and hydrodynamics[225]. On the GBR, distribution patterns of Stomatopoda remain to be thoroughly examined. Nevertheless, based on data derived from Ahyong[2], 50 percent of GBR stomatopods are shared with New Caledonia and the Chesterfield Islands, and 34 percent are shared with the Spermonde Reefs, Indonesia[2,3]. Distributions of stomatopods on the GBR often appear to be highly correlated with substrate, terrigenous input and hydrodynamics[77,225]. Though latitudinal gradients have not been analysed in detail, increasing species richness of both inter-reef and coral-dwelling stomatopods generally follows a northward trend, and this appears to also hold for most decapods.

#### *11.1.2.5 Other groups*

Information on the distribution and abundance of other benthic invertebrates is patchy. For example, polychaetes are abundant in both sediments and in reef habitats throughout the GBR. Detailed taxonomic studies exist for some families (eg Terebellidae, Nereididae). Polychaete species exhibit a range of biogeographical patterns, from occurring throughout the reef to narrow-range endemics (Hutchings unpublished data), and it is likely that these patterns will hold for many polychaete families. Whereas some species have been reported with broad Indo–Pacific distributions, closer examination usually shows this is rarely valid[142]. Soft corals on the GBR exhibit greatest diversity on mid-shelf reefs, although cover is relatively low (often less than 5%)[81]. Inshore and offshore species also occur on these mid-shelf reefs, though some species are restricted to these reefs.

Bryozoans are well represented on the GBR by more than 300 species, though this number is probably a significant underestimate[100]. Many of the ascidians found on the GBR range widely throughout the Indo–Pacific; particularly common are large mats of diademnids with algal symbionts[181].

### 11.1.3 Geographical range summary

In summary, benthic marine invertebrates on the GBR include widely distributed Indo–Pacific species, as well as species with a distinct northern or southern distribution. In each group, species with discrete distributions (narrow-range endemics) also occur. Some species occur in inshore waters

and can tolerate a wide range of environmental conditions, while others seem be limited to specific environments[82]. For example, some corals and other benthic invertebrates in the Daintree region show a remarkable tolerance for extreme turbidity and sediment load after heavy rains. Similarly, several coral reef stomatopods, such as *Gonodactylaceus falcatus*, *G. graphurus* and *Pseudosquilla ciliata* tolerate the varying salinity, turbidity and sedimentation prevalent on coastal or nearshore reefs. Other reef stomatopods, such as members of the Takuidae, occur only on reefs under a more 'oceanic' influence[77] (Ahyong unpublished data). Some sponges are well adapted to live in more turbid environments (eg mangroves[74]) and are generally more abundant and diverse in back-reef areas on the GBR (Wörheide pers obs). Similar patterns were obtained for other invertebrate groups, with species more abundant in, or restricted to, inshore muddy environments, and some infauna favouring inshore turbid environments[199]. As already indicated the distribution of infauna is heavily dependent upon sediment type and organic content, the distribution of which is related to factors such as river plumes for terrestrial-derived sediments, wave patterns, and ocean currents.

The GBR consists of a mosaic of habitats and, because the distribution of the benthos is largely driven by the availability of suitable habitat, much of the fauna consists of isolated populations. Interconnectivity of benthic invertebrate populations has not been examined on the GBR, with only a few exceptions. Populations of giant clams and crown-of-thorns starfish are genetically continuous, as would be expected from species with pelagic larvae[26,18]. Similarly, considerable gene flow exists between populations of coral species with pelagic larvae[136]. Populations of tiger prawns (several *Penaeus* spp.) in Queensland, though exhibiting a degree of sub-structuring, are also genetically continuous[106]. It is noteworthy, however, that some mollusc populations with little genetic variation on the GBR exhibit a high level of genetic differentiation between archipelagos elsewhere in the Indo–West Pacific[183], and genetic diversity may follow latitudinal gradients[26].

The origin of the GBR and its subsequent geological history are well documented (eg Davies and Hopley[67], Davies[65]). The present-day GBR is young (approximately 9000 years old), and is built on the foundations of previous GBRs (over a period of approximately 600,000 years since the mid-Pleistocene[222]. Reef growth initiated on the Marion Plateau post–early Miocene (23 million years ago) (Davies[66] and literature cited therein) and successive GBR ecosystems are not necessarily identical owing to the great differences in pathways and processes that influence connectivity between the biota over geological time (eg Cappo and Kelley[43] and literature cited therein). Certainly, the cyclical rise and fall of sea level after the glacial low stand 18,000 years before present (Larcombe et al.[164] and literature cited therein) had major impacts on connectivity and distribution of marine biota on the GBR by leaving large areas of the GBR exposed, dry and unsuitable for marine organisms. A comparison of drill-core data from around Lizard Island with sea-level curves for northeast Australia indicated rapid reef initiation (within 500 years) at Lizard Island after flooding of the granite basement about 6700 years before present[222].

### 11.1.4 The role of benthic invertebrates on the GBR

Benthic marine invertebrates play a variety of roles in the GBR. Macrofaunal activity in sediments is important in global nutrient cycling and transport, transport of sediments, processing of pollutants, and secondary production including commercial species[257], though these roles are rarely quantified. The macrofauna, as already mentioned, encompasses a tremendous diversity of phyla.

The component species exhibit a range of feeding and reproductive cycles, and are important food sources for groups at higher trophic levels, including fish, many commercial species of crustaceans and intertidal wading birds.

Inter-reef areas are rarely a homogenous habitat of sediment. Rather, they are a mosaic of sediments and isolates of sponge, gorgonians and molluscs that provide substrate for many mobile species, including fish. Only in areas that have been subjected to heavy trawling will such important habitats be absent[140].

Sponges are an important component of macrobenthic communities on hard substrates, as well as small isolates on soft substrates. They continuously filter water, removing bacteria and dissolved organic and particulate organic matter. However, recent studies clearly show that these cryptic communities are pivotal in nutrient and carbon cycling on the reef[224,226]. In addition, recent initiatives to establish viable aquaculture of commercial bath sponges in the Torres Straits, in collaboration with local indigenous people, highlight their socio-economic importance. Sponges also provide shelter and microhabitats for other fish and invertebrates[c,120].

Echinoderms also play important roles in the GBR, particularly as bioturbators and predators. Aspidochirotid holothurians are benthic deposit feeders and are prominent members of the soft-sediment benthos[275,276]. Burrowing species are particularly important in bioturbation and oxygenation of the nutrient-poor carbonate sediments that dominate much of the GBR[274,275,276]. Loss of these holothurians from lagoon and inter-reef areas therefore, is likely to affect sediment–ecosystem processes[275,276]. The influence of crown-of-thorns starfish on the ecology of macrobenthic communities on the GBR is probably one of the most important among the invertebrates[185,61,149].

Molluscs act at all trophic levels: as prey, predators (including carnivorous, herbivorous, deposit-feeding, filter-feeding and verminivorous species), parasites, and hosts (for symbiotic or parasitic organisms). Like some echinoderms and crustaceans, infaunal molluscs are important bioturbators, such as *Cerithideopsilla cingulata* in subtropical mudflats[152]. Bivalves may be particularly important to some reef or inter-reef communities because many are filter feeders able to improve water quality. For example, giant clams from Tonga weighing 850 grams, can filter up to 600 ml of water per minute[160]. Since filtration rates largely depend on body size[160], *Tridacna maxima* and *T. squamosa*, the species of giant clam most common on the GBR, can be expected to filter water at a similar rate based on their similar size. Gastropods and bivalves include some of the engineers of the reef, acting as builders through the remains of their calcified shells[299], as architects through their boring behaviour that provides habitat for cryptofauna[186], and as demolishers through boring behaviour or predation that can weaken coral attachment[58,232]. Several GBR species of molluscs are also aquacultured or commercially harvested for food (eg *Trochus* sp., scallops, squid)[290,301], nacre (eg *Trochus niloticus*)[301], or whole shells (eg *Strombus* sp., *Conus* sp., *Volute* sp.) (see Weis et al.[285] for comprehensive list of species collected for their shells in Queensland). The most popular species in the Australian specimen shell trade are by far those in the Cypraeidae, followed by the Volutidae and Haliotidae[210].

Crustaceans are also important at all trophic and ecosystem levels. For example, copepods are important grazers and a major food source for larval and adult fish[111]. Burrowing decapods, particularly thalassinideans and alpheid shrimps are significant bioturbators[189]. Peracarids and other

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[c] http://www.crctorres.com/research/T1-6.html

micro crustaceans are significant for their scavenging, detrital recycling and low trophic position[155,154]. Decapods and stomatopods are commercially harvested from inter-reef areas throughout the GBR. Some of the most important commercial decapods (namely crabs and prawns) are opportunistic feeders, being both predatory and facultative scavengers[284]. Stomatopods and many decapods can be high-level predators in all habitats[2], and are in turn preyed upon by pelagic fish (as larvae) and demersal fish (as adults).

Loss of marine invertebrates will have major socio-economic consequences in terms of commercial and recreational fisheries and tourism with many divers and photographers fascinated by marine invertebrates, especially nudibranchs[4] and flat worms[191].

Many benthic invertebrates are also a rich source of bioactive compounds with various medicinal, industrial and commercial applications. Sponges, bryozoans and ascidians are the major source of toxic secondary metabolites in the sea[188] and therefore have been the prime target for research[84]. Other marine invertebrates, such as nudibranchs, have the ability to sequester and modify compounds obtained from dietary sources, thus providing even more potential for useful bioactive compounds from benthic invertebrates[53,204]. Some evidence indicates that bioactive compounds of certain invertebrates may vary according to region and even reef[83]. These compounds are likely dependent on food sources, changes to microbial faunas across small environmental gradients, or seasonally changing habitat conditions.

## 11.2 Vulnerability of benthic invertebrates to climate change

Whereas individual components of climate change are discussed below, in reality, benthic invertebrates will be subjected to several concurrent stressors that may exacerbate the effect of other stressors (see section 11.3.2). For example, a species that is already stressed by rising temperatures will probably be far more susceptible to other stressors, such as ultraviolet radiation (UVR) and salinity extremes[125,218]. In many cases, the extreme events will have greatest impact on individuals. Lough (chapter 2) provides ranges of predicted changes, and much greater changes may occur at particular sites with impacts varying during the year and their effects varying according to the life stage of the organism. In addition, the speed of change is important for all the factors considered, and detailed predictions are not available generally, let alone for particular sites. These factors make assessing the vulnerability of the tremendous diversity of marine invertebrates on the GBR extremely difficult and imprecise.

### 11.2.1 Exposure

#### *11.2.1.1 Ocean circulation*

Currently, there is no consensus on whether the direction or strength of currents within the GBR will change, although it seems highly likely. The GBR is presently dominated by two large-scale global circulation systems: the south-easterly trade wind circulation, and the Australian summer monsoon westerly circulation. These effectively divide the year into the warm summer wet season (October to March) and the cooler winter dry season (April to September). Any changes to these circulations have the potential for major impacts on the recruitment of benthic invertebrates, many of which have pelagic larvae. If established current variations[265] occur earlier or later in the year, larval dispersal may be affected as well as food availability for pelagic larvae. Changes in water currents may also impact food availability for many of the filter-feeding organisms in benthic communities (McKinnon et al. chapter 6) in terms of abundance and quality of available food, shifting water masses of different temperatures and the influence of increased runoff.

### 11.2.1.2 Water temperature

Sea surface temperatures (SSTs) have increased on the GBR, although not uniformly, with the degree of increase being greater in winter than summer and greater in the central and southern regions than the northern GBR. Projected rises are 1 to 3°C and it seems likely that SST extremes will change and follow air temperature extremes. Certainly, increased incidences of coral bleaching are evident, often leading to the death of corals and associated fauna, thereby modifying coral reef communities. While effects will be greatest in shallow waters, increased temperatures will be transmitted through the water column with effects decreasing with depth.

In addition to increasing SSTs, the number of days with temperature extremes is also on the rise. The GBR is already experiencing a greater number of more extreme hot days and nights, and fewer cold days and nights with respect to air temperature (Lough chapter 2). Coastal air temperatures are predicted to rise by 4 to 5°C by 2070, although not uniformly along the GBR. For example, at the offshore Myrmidon Reef automatic weather station, average daily SSTs ranged from a minimum of 24°C in the last week of August to a maximum of 29°C in the first week of February (4.8°C range)[d]. However, the difference between the minimum and maximum observed daily SSTs is 9.5°C, so local extremes are likely to have significant effects on intertidal and shallow water species[217] with effects varying along the coast.

### 11.2.1.3 Light spectra

Changes in water temperature and storm events may affect dissolved organic carbon and particulate matter, which will in turn modify the attenuation of light and UVR in a given region[244]. Recent analyses suggest that turbidity accounted for 74 to 79 percent of variation in light irradiance in a shallow subtidal coral reef, with increasing attenuation at depths[9]. In addition, recent evidence suggests that climate change may delay recovery of the ozone layer[245], and ozone depletion may be linked to more rapid climate change[117], thereby exposing intertidal and shallow-water organisms to longer periods of human-increased UVR.

Species living in intertidal and shallow water will be most vulnerable to changes in light attenuation and UVR exposure, especially those with symbiotic algae such as giant clams[75], sponges[122], anemones[278,75] and those spawning in intertidal habitats exposed to full sun[218].

### 11.2.1.4 Physical disturbance (tropical storms)

In the past 30 years the number of cyclones affecting the GBR may have declined, but those that do occur are more intense[192] (Lough chapter 2). Predicted enhanced greenhouse conditions include both warmer SSTs and changes in the atmospheric temperature profile with a 5 to 12 percent increase in wind speeds and higher rainfall. It is unclear, however, whether there will be changes in location

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[d] For further information, see http://www.aims.gov.au/pages/facilities/weather-stations/weather-index.html

and frequency of tropical storms and to what extent they will be modulated by El Niño–Southern Oscillation (ENSO) events. Increased intensity of storm events will disturb or destroy reef habitats, especially in shallow and coastal waters. Associated increases in storm surge will also impact on shallow coastal communities. These impacts will be compounded by rising sea level (see 11.2.1.5).

Although it is unclear how rainfall patterns will change along the GBR coast, rainfall patterns and river flows are projected to exhibit greater variation between wet and dry years than in the past, with spatial and inter-annual variability modulated by ENSO and Pacific Decadal Oscillation (PDO) (Lough chapter 2).

The most vulnerable groups of organisms during storm activities, with associated increased river flow and sedimentation, are sessile species or egg masses in the intertidal or shallow subtidal which are physically torn from the substrate or buried, and infaunal organisms that are physically dislodged by wave action that erodes the habitat. Both groups have difficulties in reattaching themselves or reburrowing into the sediment before being washed out to sea, onto unsuitable habitats or stranded on beaches[294]. A general trend of shifting community structure with increasing sedimentation or resuspension has been observed for sponges[16,44]. Similarly, fluctuations in sediment load were partly responsible for changes in the structure and composition of sponge assemblages on tropical rocky shores in the Bay of Mazatlan (Pacific Ocean, Mexico)[44], and in a New Zealand study, sediment levels of more than 0.5 cm precluded settlement. Re-settlement success appears to be inversely correlated with sediment depth[16]. For the temperate reef sponge *Cymbastella concentrica*, increased siltation led to a reduction in weight and a lower reproductive activity[230]. It has also been shown for Caribbean sponges that strong storms (hurricanes) have a dramatic impact on sponge communities, with loss of nearly half of the individuals and biomass in San Blas (Panama) during Hurricane Joan in 1988[298].

### *11.2.1.5 Ocean acidification and sea level rise*

The oceans are becoming more acidic owing to absorption of anthropogenic carbon dioxide from the atmosphere[175,198,238,159]. The long term natural variability of oceanic pH is unknown, but can be inferred through study of coral skeletons[206]. A recent study of boron isotopes in coral from the southwestern Pacific provided evidence that large variations in pH have occurred over approximately 50 year cycles and that these natural pH cycles can modulate the impact of ocean acidification on coral reef ecosystems[206,180]. In addition, efficient lagoon flushing is required for reef water to achieve pH equilibrium with the open ocean[206]. Thus, effects of predicted progressive acidification of the ocean on coral reef communities will differ among reefs depending on natural cycles and degree of reef flushing.

It is expected that ocean acidification will have a major impact on organisms such as molluscs and echinoderms that use calcium carbonate for skeletal support of their bodies[162,250]. Other groups likely to be affected are foraminifera, soft corals and sea fans, as they also incorporate calcium carbonate into their skeletons. Calcification rates are depressed at lower pH and are influenced by temperature[162]. Conversely, some speculate that sea warming might stimulate increased calcification through enhancement of the physiological processes involved, potentially ameliorating the effect of acidification[176,158,159]. The predicted impact of ocean acidification on coral reef invertebrates is controversial and a consensus is unlikely to be reached in the short term[176,158,206,159,180]. Any changes to structure or density of coral skeletons, however, could impact the infaunal communities associated with either living or dead coral[138].

If the presently observed rate of sea level rise continues to 2100 then global sea level would be 310 ± 30 mm higher than in 1990, and this rate may accelerate over time[52]. Certainly, there will be regional variations along the GBR as the coastal topography and islands will determine the influence of tides and extent of inundation, in addition to modulation by ENSO events. The regional projection for sea level rise is 0.1 to 0.9 metres by 2010 (Lough chapter 2). The communities most vulnerable to sea level rise will be intertidal, seagrass and mangrove communities (Waycott et al. chapter 8, Lovelock and Ellison chapter 9 and Sheaves et al. chapter 19). Benthic invertebrates associated with live corals in shallow water are potentially vulnerable if these coral colonies fail to keep up with rising sea level.

## 11.2.2. Sensitivity

### 11.2.2.1 Ocean circulation

Changes in ocean circulation have the potential to disperse larvae over unsuitable habitats for settlement. The process of settlement is critical for many invertebrates, especially for sedentary or sessile species, and a clear correlation has been observed between the time propagules spend in the water column and dispersal distance[246,247]. If larvae are dispersed over unsuitable habitat, they will fail to metamorphose and settle. Even if they can delay settlement, this is only an option for a limited time[205]. Species with short larval periods are most likely to be directly affected by changing ocean currents through dispersal to unfavourable sites or areas with a lower concentration of larvae, while those with longer larval periods or direct development may be more tolerant to changing currents because they will presumably be able to delay settlement until they arrive at a suitable habitat. For example, *Littorina saxatalis*, which releases brooded juveniles, is more widespread than the planktotroph *L. littorea*. This supports the hypothesis that species with long-lived larvae may be vulnerable to problems associated with current mediated dispersal, including a settling population too low to be viable (Johannesson[148] and literature cited therein). Filter-feeding organisms may also be affected by changes in current patterns, as the quality or abundance of their food supply in the water column may change.

### 11.2.2.2 Water temperature

Rising water temperatures will certainly impact on benthic invertebrates, but the degree of impact will vary between species and range from little impact to death. We have little precise information on lethal threshold temperatures, but we do know that water temperature affects metabolic rate and the timing of reproduction for some groups, including sponges[89,90], ascidians[15,163], molluscs[268], and polychaetes[98]. Increased temperature, in concert with other stressors like sedimentation, increased nutrients and physical damage will contribute to an increased abundance of certain sponge groups (eg boring sponges) and has been found to be responsible for decreases in live coral cover on a reef studied in Belize (Caribbean Sea[239]). However, no relationship between warm water incursions and bleaching of the sponge *Xestospongia muta* has been observed (J Pawlik pers comm).

It is predicted that extremes in water temperature will increase, which are likely to have significant effects both on survival of larvae and adults, as well as affecting growth and reproduction. The sensitivity of a species to thermal changes will probably vary geographically. Changes are predicted to be greatest in the central and southern part of the GBR, so species occurring in these areas are most likely to be impacted.

Development and growth rates of marine invertebrates are strongly and positively correlated to temperature[93,200,150]. The strength of this relationship will depend on life history characteristics that will determine exposure to thermal fluctuations and extremes. For example, developmental rates of species that spawn in exposed habitats, during low tides, or daytime may be more affected by temperature changes and extremes than species that spawn in sheltered habitats, during high tides, or at night[216].

Development of larvae influences the thermal history of the population and spawning season[93,150]. Increased temperature may reduce dispersal potential by accelerating growth rates and reducing time spent in the water column, thereby potentially limiting or reducing gene flow between otherwise connected populations[195]. Isolation of populations could render them more susceptible to localised extinction.

### 11.2.2.3 Ocean acidification

All marine biota that have calcareous skeletons are sensitive to ocean acidification because carbonate saturation, which is related to pH, has a major effect on calcification rates[157,159]. The predicted decrease in ocean pH by 0.4 to 0.5 pH units by 2100 may impact on the ability of invertebrates to secrete protective skeletons[85]. The biota most sensitive to ocean acidification includes a broad suite of calcifying organisms including molluscs[184], echinoderms, crustaceans, bryozoans, serpulid polychaetes, foraminifera[119] and some species of sponges, particularly at ocean conditions with pH lower than 7.5[184,119]. These organisms have evolved the protective use of a shell or calcareous skeleton. Predicted changes in ocean pH will negatively affect shell and skeleton formation, development and strength, thereby affecting their primary function, as protection from physical damage, including predation. Indeed, recent modeling suggests that molluscs evolved optimal shell morphologies in response to predators[145], so any weakening of the shell may increase risk of predation. Calcification studies of gastropods and sea urchins indicated that a 200 parts per million increase in carbon dioxide ($CO_2$) in sea water adversely affected growth[250].

### 11.2.2.4 Light spectra

Spectral changes associated with increased turbidity, sedimentation, and storm frequency will impact benthic invertebrates that obtain at least part of their nutrition from photosynthetic symbionts (eg giant clams[75] and anemones[278]). Sensitivity to turbid conditions will likely be species-specific, with some species able to switch to heterotrophy for long periods, thereby adapting to turbidity and increased light attenuation[8].

Sponge-zooxanthellae associations appear to be more stable than coral-zooxanthellae associations, at least in some hadromerid sponges[122]. Although sponges bleach less frequently than adjacent corals[281], completely bleached individuals ultimately die[91]. A recent study of bleaching of *Xestospongia muta* in the Caribbean, however, suggests that cycles of bleaching are not necessarily deleterious (J Pawlik pers comm).

Increased UVR exposure may also negatively affect species without adequate or adaptive behavioural or chemical protection. Sessile organisms (such as didemnid ascidians) or those unable to detect UVR will be more vulnerable than species able to move away from damaging UVR. Marine animals obtain chemical sunscreens called mycosporine-like amino acids (MAAs) from symbioses or diet[249].

In the latter case, photoprotective function cannot be intrinsically induced. Therefore, animals that rely heavily on MAAs for protective function, but obtain these solely through their diet, may be particularly vulnerable to increased UVR exposure.

### 11.2.2.5 Sea level rise

Rising sea level has the potential to inundate obligate intertidal species and shallow seagrass beds and adjacent mangroves (Waycott et al. chapter 8, Lovelock and Ellison chapter 9), which are home to diverse benthic marine invertebrate communities. Impacts will depend on the magnitude and rate of such changes. If the rate of change is slow, then seagrass communities and associated benthic communities have the potential to expand into shallower water. Conversely, loss of deep seagrass and conversion to a sandy or muddy substrate will drastically change invertebrate community composition.

Sea level rise may also affect benthic communities that are relatively isolated by geographical barriers by facilitating larval dispersal. The effect of geographical barriers could be reduced with heightened sea level, resulting in recruitment of invader species to a formerly isolated area[17]. Alternatively, increased larval dispersal between previously semi-isolated intraspecific populations could also help to maintain genetic continuity.

Coral communities (Hoegh-Guldberg et al. chapter 10) will be affected by sea level rise, which in turn will alter available substrate and affect other dependent benthic invertebrates[11]. Bioeroders, such as boring sponges[228], have further potential to destabilize the reef framework, making it more vulnerable to fatal storm damage.

### 11.2.2.6 Physical disturbance

Sessile organisms are vulnerable to detachment via physical disturbance. The magnitude of these effects will depend on their ability to reattach or withstand periods of detachment (eg Wilson[294]).

### 11.2.2.7 Rainfall and river flood plumes

Marine benthic invertebrates can be highly sensitive to changes in salinity (eg encapsulated molluscs[216]) and many species have, at best, a limited ability to osmoregulate in the presence of freshwater[194]. Different life stages usually have varying sensitivities with newly settled recruits the most vulnerable (see Webster and Hill chapter 5). Some species may be able to avoid this stressor by burrowing deeper into the sediment where salinity changes are reduced, and others can close their shells to exclude fresh water, but these reactions can only be sustained for short periods during which no feeding can occur. Reactions to flooding and salinity changes are likely to be species-specific within most groups. For example, recent studies show that two colonial ascidians with similar life histories show different tolerances to low salinities (E Westerman pers comm). Sponges also seem to be affected by salinity changes, with evidence of decreased growth rates and lower reproductive activity[230]. In addition, the size of the banana prawn harvest in the Gulf of Carpentaria and eastern Queensland strongly correlates with rainfall[263], while reproduction and activity of the blue swimming crab is negatively affected by low salinity[209,212]. Echinoderms are probably the most stenohaline of the benthic groups, with limited tolerance to decreases in salinity, particularly amongst the larvae[182]. In summary, the timing and duration of salinity reductions will be critical and effects will vary among taxa.

## 11.2.3 Impacts

### *11.2.3.1 Ocean circulation*

Changes in ocean circulation can affect food availability to suspension feeders[287], larval supply and upwelling. Food availability is an important factor controlling reproduction in some marine invertebrates (eg egg production in the ascidian *Botrullus schlosseri*[108], so changes in ocean circulation may have significant impacts on reproduction, larval survival and species ranges.

If larvae are dispersed to unsuitable habitats, and adults subjected to suboptimal current patterns, present species ranges could be significantly altered. Changes in circulation and upwelling, with downstream effects on primary productivity, will not only have implications for larval survival and recruitment, but also food availability for filter feeding animals such as crinoids, sponges, ascidians and many epifaunal bivalves.

Certain groups of molluscs may be more resistant to extinction as a result of changes in ocean circulation pattern. Examination of the distribution of narrow-aperture rock-dwelling gastropods, based on museum collections, has revealed that they are not significantly affected by deep-sea barriers in the Indo–West Pacific, a finding consistent with the resistance to extinction and high level of recent speciation of this group[279].

### *11.2.3.2 Water temperature*

Although little data exist on current geographic range changes in the GBR for most benthic invertebrates, the fossil record of molluscs indicates that water temperature has indeed played a major role in migrations and extinctions of many species, particularly in conjunction with sea level changes[121]. Some species have extended their range during warmer periods (eg Australian species introductions to New Zealand during the Pleistocene[17], northward extension of *Venericardia procera* in the southwestern Atlantic during the late Quaternary[1]. Other species presumably were unable to adapt to climate change and became locally extinct (eg the extinction of *Tegula atra* in the southwestern Atlantic during the late Quaternary[1] or completely extinct (eg many molluscs in the southern hemisphere during the Cretaceous-Tertiary extinction event and associated climate change[264]. In contrast, Jackson and Sheldon[147] suggest that temperature fluctuations and sea level change have had little impact on species composition of molluscs and corals in the fossil record throughout tropical America. They suggest that there is no correlation between the magnitude of environmental change and the subsequent ecological and evolutionary response, although the speed of change was much slower than what we are currently observing. While fossil coral communities have been studied in detail in the GBR[201], associated benthic invertebrates have not. Jackson and Johnson[146] point out that the excellent marine fossil record and the similarity between ancient and current species provides a great opportunity to investigate effects of environmental change on communities and ecosystems, but 'unfortunately, this potential has not been fully exploited because of lack of well-sampled time series and adequate statistical analysis'. As ecological communities were profoundly altered by human activity long before modern ecological studies began, Jackson and Johnson[146] suggest that data from the Holocene should be considered the only standard for 'pristine' communities prior to human impact.

The wide variety of reproductive strategies in many benthic invertebrates makes generalisations on timing of reproduction difficult. For some species, such as the broadcast spawning sponges

*Xestospongia bergquistia* and *X. testudinaria*, spawning was observed during periods of warm water just prior to water temperature reaching its maximum[90]. However, larval release in other species is not predictable, as in the viviparous sponge *Leucetta chagosensis* (Wörheide pers obs), or occurs year-round, as in the brooding shallow water sponge *Amphimedon queenslandica* (formerly referred to as *Reniera* sp.[168]. Similarly, molluscan reproductive patterns are often unpredictable or species-specific, with no obvious relationships with taxonomy or avoidance of thermal stress[219]. Most echinoderm species appear to spawn in summer and can be induced to spawn in response to temperature fluctuation[220,54]. Some species with benthic development, including a new species of *Aquilonastra* from One Tree Island, lays its eggs in masses on intertidal rubble in winter, potentially as an adaptation to avoid the effects of high temperature on embryonic development, similar to that exhibited by closely related non-tropical species[34]. Many of the most abundant aspidochirotid sea cucumbers on the GBR including *Holothuria* species and *Stichopus chloronotus* have distinct summer and winter patterns of sexual and asexual reproduction. They spawn gametes in summer and exhibit a peak in clonal reproduction by fission (splitting in half) in the winter[113,167].

Rising water temperature will almost certainly lead to species spawning earlier or for longer periods (eg ascidians, E Westerman pers comm) and may affect larval recruitment success. In the case of species producing planktotrophic larvae, this may not necessarily coincide with phytoplankton availability. This temporal separation of zooplankton and the phytoplanktonic food source is reported in the Atlantic and attributed to climate change[118]. In addition, species requiring other benthic organisms to provide cues for metamorphosis or food for juveniles may also fail to spawn at an optimal time. For example, some nudibranchs are specialised feeders on a single species of sponge, ascidian or bryozoan. Changes in spawning behaviour may therefore negatively affect larval metamorphosis or juvenile feeding if these substrates are not readily available.

Rising water temperature and associated factors are likely to affect larvae more than adults. Though not a tropical ecosystem, increased ocean temperatures correlate with zooplankton decline in the California Current[233]. Meroplankton (species in plankton for only part of its life cycle) seem to be more vulnerable to warming water than holozooplankton (species in plankton permanently)[118], providing support to the hypothesis that larvae of marine invertebrates are more vulnerable to changing temperatures than adults. Any impact studies should therefore account for larval stages (McKinnon et al. chapter 6).

On temperate shores, Fitzhenry and Podolsky[87] found that increasing temperatures impacted negatively on reproductive success of the barnacle *Chthalmus fragilis*. Populations of species at the boundary of their temperature tolerances will either die due to elevated temperatures, fail to breed, or in some way modify their physiological processes such as respiration, growth and reproduction to adapt to the new conditions (eg molluscs[1]). Temperature also affects key metabolic enzymes in littorinid molluscs, with variations found in populations at different latitudes and shore levels[259] and similarly in the bivalve *Mytilus edulis*[49].

Species that only occur in far northern regions of the GBR may extend their populations further south with rising temperature. Range extensions into warmer waters have been documented in the northern hemisphere both through the fossil record (eg Aguirre et al.[1]) and through research on current populations (eg Hiscock et al.[123]). Obviously, migration of species is only feasible for mobile

organisms, but the pelagic larvae of sedentary or sessile species may settle further south or in deeper water and change distribution ranges. While boundary changes are yet to be documented for any Australian reef species, Barry et al.[14] and Sagarin et al.[240]) found climate-related long-term faunal changes for Californian rocky intertidal communities after only a 0.75°C increase in water temperature and a 2.2°C increase in air temperature. Similarly, the dramatic decline in mussel beds along the California coast is attributed to warming waters. Note, however, that a recent comparison of late Pliocene and present-day molluscan assemblages from Cornwall in the United Kingdom suggests that climate change will not affect overall richness in this region, although species composition will change[283]. No similar comparisons have been made with the molluscan fossil record in the Indo–West Pacific. In other temperate areas there is also good evidence of intertidal communities changing with increases in both air and sea temperature[243].

If water temperature increases persist for only a short time (eg a few days), some benthic burrowing species may avoid unfavorable conditions by burrowing deeper where temperature changes are lower (eg amphipods[272]), and others by reducing their metabolism (eg ascidians[15]). Their continuing survival, however, will depend on the frequency and timing of warming events, especially in relation to life cycles, with certain stages more vulnerable.

Recent research also suggests that ocean warming can facilitate the establishment and spread of invasive species. Stachowicz et al.[262] compared distribution patterns of ascidians with ocean temperature over 12 years and found that introduced species recruited earlier in warmer years, while native species showed no such relationship. Laboratory studies revealed that two invasive ascidian species grew faster than native species, but only at the warmest summer temperatures, suggesting that community changes due to climate change are primarily the result of changing temperature extremes, rather than annual mean changes[262]. The order of species recruitment has a huge effect on community structure. Warmer water temperatures can facilitate earlier colonisation by invaders and associated community shifts to dominance by invaders[262].

### *11.2.3.3. Ocean acidification*

The impact of ocean acidification on marine invertebrates will depend on the rate of change of seawater pH, relative to its natural variability[206]. It is expected that the impacts of ocean acidification will be greatest in surface and shallow water[41]. Current knowledge of the biology of skeleton formation indicates that the predicted changes in ocean pH by 0.4 to 0.5 units by 2100 may impact the ability of marine invertebrates to secrete protective skeletons. Existing skeletons may be weakened, providing less protection from predators and physical damage from trawling and storm activity, and less resistance to other physical factors, such as desiccation in the intertidal[238,162]. Impaired skeletogenesis is expected to compromise survivorship of both planktonic and benthic life stages of coral reef invertebrates[162]. The larval skeleton of gastropods, sea urchins and other benthic invertebrates are particularly fragile and may not be produced under acidic conditions[162]. This may result in complete recruitment failure of a whole suite of benthic invertebrates. In addition, some organisms may also show indirect effects of ocean acidification by diverting resources from their shells towards improving physiological function. For example, the bivalve *Mytilus galloprovincialis* dissolves its calcium carbonate shell during periods of prolonged hypercapnia in order to increase haemolymph bicarbonate and limit acidosis[184].

Increased carbon dioxide in surface waters has also been shown to lower metabolic rate in benthic invertebrates[184]. This may impact populations by affecting feeding, growth and reproduction.

### 11.2.3.4 Light spectra

Increases in light attenuation associated with increased turbidity and sedimentation will negatively affect organisms with photosynthetic symbionts. For example, turbid conditions with reduced light availability are known to impair the physiology of the giant clam *T. gigas*[75]. The relationship between turbidity, heterotrophy and autotrophy is well studied among corals and their photosymbionts[8,79], but the effects of turbidity on most non-coral photosymbionts remain unknown. Under turbid conditions and sedimentation, the effects on corals can result in a switch to heterotrophy[8], reduced growth[300], or even expulsion of zooxanthellae[286]. The latter case may have serious consequences for the host, including death[256,286]. Increased turbidity on coral reefs may also result in shifts in the bioeroding communities from sponges to bivalves and polychaetes[177].

### 11.2.3.5 Sea level rise

Sea level rise may affect current coral reefs by shifting coral recruitment to 'new' shallow waters. This will affect distributions of other benthic invertebrates associated with corals.

Data derived from the mid to late Holocene record of a southeastern Australian lagoon indicates that sea level fluctuations and associated changes in sedimentation caused community change in estuarine and intertidal environments, with a shift from dominance by molluscs and foraminifera to charophytes, associated with a sea level drop and closure of the lagoon[94]. It is currently unknown how community dominance will shift on the GBR with sea level rise but, as mentioned previously, the biggest impacts will most likely occur in shallow, intertidal, and estuarine zones.

In addition, recruitment of benthic invertebrates to localised areas may be impacted if current geographic barriers to larval dispersal are bridged by sea level rise. Ben[17] found evidence of this phenomenon on a much larger and dramatic scale with the Pleistocene extinction of 29 species of molluscs and the introduction of warmer water species in New Zealand after the breach of the Auckland isthmus caused by rising sea levels[17]. Obviously, no such similar formidable geographic barrier exists on the GBR, but sea level rise may breach smaller barriers to facilitate dispersal of larvae currently isolated from areas. This could result in local introductions of species and possibly competition-mediated extinctions, but could also help maintain genetic continuity between previously semi-isolated intraspecific populations.

Although global climate change is usually discussed only in terms of its negative effects, sea level rise may have a positive effect on the benthic invertebrates of coral reefs. Sea level has remained relatively static for the past several thousand years, and coral reefs have therefore reached an elevation where continued upward growth is constrained by sea level[256]. As sea level rises, this constraint is removed, ultimately increasing the availability of coral substrate for benthic invertebrates. As a result, invertebrate diversity in some lagoon environments may increase. Whereas current conditions ensure lagoon communities are limited by stressors associated with ocean circulation (eg salinity extremes or nutrient depletion), sea level rise may affect water circulation in these environments such that conditions more closely represent the open ocean[256].

### 11.2.3.6 Physical disturbance

Increased storm activity will also indirectly impact inshore communities through more frequent mass flooding and increased runoff. These storm events may temporarily or permanently increase localised turbidity and freshwater input. In addition, direct impact of storms and higher sea levels may fragment fringing reefs, reducing their wave-breaking ability, leading to changes on island or mainland beaches[248]. With increased storm intensity, it is predicted that flood plumes will be larger and extend further offshore (see section 11.2.3.7). Sediment distribution, critical for many benthic infaunal organisms[141], may be altered in the short term by storm events, especially in shallow water, and in the long term by altered hydrographic regimes. The amount of change will depend on the nature of the sediment, with fine sediments most easily disturbed and resuspended leading to increased turbidity. Changes in turbidity will affect certain specialist faunas such as phototrophic sponges, which are sensitive to light and turbidity changes[288] (see section 11.2.3.4). Octocorals are susceptible to abrasion, dislodgement by storm waves, movement of sand and rubble[80], and during extreme events communities can be decimated.

### 11.2.3.7 Rainfall and river flood plumes

Freshwater plumes can be lethal to marine invertebrates, depending on the duration and resulting salinity. Increased monsoon activity on the northern GBR could well result in decreased seasonal salinity. Reduced salinity can be lethal to octocorals and other invertebrates on reef flats emersed at low tide during heavy rain or in freshwater lenses of river plumes[80]. Community changes among colonial ascidian communities along the eastern United States have been with reduced salinity. After heavy flooding, sessile assemblages were dominated by the tolerant *Botryllus schlosseri*, in contrast to the normal mixed communities of *B. schlosseri* and *Botryllouides violaceus* (E Westerman pers comm). Even more concerning is the fact that *B. violaceus* is a recent invader and seems better adapted to changing and extreme environmental conditions than native species or less recent arrivals. The GBR may be similarly vulnerable to sessile invasive species with greater salinity tolerances.

Benthic organisms may also be indirectly affected by rainfall and river flood plumes in terms of food availability. Effects of rainfall on plankton will affect food availability for pelagic larvae, filter feeders and deposit feeders, as well as organisms higher up the food chain. Indeed, freshwater influx can negatively affect plankton abundance. For example, around Pulau Seribu, Indonesia, zooplankton composition showed significant seasonal differences[10], and zooplankton volume decreased during the wet season[213].

Increased levels of sedimentation can negatively affect rates of photosynthesis in octocorals[223] due to light absorption by particles deposited on the colonies or suspended in the water column. In the Caribbean, mass mortality of gorgonians was recorded after large river floods importing high sediment loads[95] and in some cases the fungus *Aspergillus* was exported from the land to the inshore waters. Mass mortality of *Gorgonia ventalina* and *G. flabellum* has been observed[253,190]. On the GBR, flood plumes often contain nutrients, top soil and pesticides, which impact negatively on octocorals, making them more susceptible to fungal infections, colonisation by algae, barnacles, bryozoans or anemones. Often high levels of partial mortality occur in colonies[80]. It seems likely that other colonial organisms or sessile invertebrates will be similarly affected.

## 11.2.4 Adaptive capacity

### 11.2.4.1 Water temperature

Analyses of the fossil record have revealed broad patterns indicating the adaptive capacities of molluscan groups to broad-scale change. During the Cretaceous-Tertiary extinction event, molluscan deposit feeders in the Southern Hemisphere were the group most resilient to changing environmental conditions, but this depended on life history characteristics and habitat[264]. Suspension-feeding molluscs, on the other hand, exhibited the highest extinction rate[264]. Of all molluscan groups, bivalves from genera with large horizontal and vertical ranges had the highest survival rate, while carnivorous gastropods with planktotrophic development showed the highest rate of speciation[264]. Responses of these taxa to water temperature and currents may be paralleled by GBR species, based on similar feeding mechanisms, developmental mode and phylogeny.

Species can move into colder and deeper water or into cooler waters of higher latitudes (eg the bivalve *Venericardia procera*[1]), but this is an option only for species with planktonic larvae or mobile adults, and where suitable habitat is available. Sessile or colonial animals that rely largely on asexual reproduction will be severely hampered. Some species of octocorals, when bleached by increased water temperatures, are able to survive for several months, while colonies shrink to small sizes and undergo fragmentation to produce a large number of new recruits[80].

Several sponge species that occur on the GBR range further south to the subtropics (eg calcarean *Leucetta chagosensis*[297]). Recent analyses[128] have found several major species turnover points along the eastern coast, with one around the Tweed River (border of New South Wales and Queensland) separating the northeast and southeast Australian bioregions. Indeed, it was reported that in the Moreton Bay/Stradbroke Islands region, tongues of warmer tropical and cooler temperate waters overlap with the consequence that the fauna contains a spatially discrete (vertically stratified) mix of temperate (greater than 30 metres depth) and tropical (shallower water) species[64]. However, there is no direct evidence that those tropical sponges can successfully reproduce there, although they may be capable of doing so as water temperatures increase in the future. Similarly, many molluscs occur across both tropical and subtropical regions. Indeed, egg masses of a few species with typically tropical distributions, such as the cowrie, *Cypraea erosa* and the sea slug, *Berthellina citrina*, have been found in temperate waters as far south as Wollongong (Przeslawski pers obs). Numerous tropical crustaceans also regularly range into New South Wales and many are reproductive south of the GBR. Several tropical echinoderms also have a wide distribution, from the northern GBR to as far south as the Solitary Islands in New South Wales[237] (Byrne unpublished data) suggesting that some species will migrate further south.

Colonisation of the southern GBR by ophiuroids will depend on the presence of suitable habitat, and the rubble banks at One Tree Reef and other locations in the southern GBR are likely to provide the habitat required by these species. One species that is likely to expand its range on the GBR in conjunction with warming is the tropical brittle star, *Ophiocoma scolopendrina*. This is probably the most abundant ophiuroid throughout the Indo–Pacific, where it forms dense aggregations in intertidal reef flat, rubble and sand/rubble habitats[40,193]. It is highly fecund and has a planktotrophic larva with a probable two to three week dispersive phase[54]. *Ophiocoma scolopendrina* seems to be an opportunistic species but, as a specialist of the intertidal, is a heat-tolerant (eurythermal) species[193].

At present, this brittle star is locally superabundant in shallow water on Lizard Island and elsewhere in the northern GBR, but is only occasionally encountered on the southern GBR (Byrne unpublished data). Although a southward expansion is likely, it is not clear how it may respond to warming of the northern regions of the GBR. *Ophiocoma scolopendrina* is a robust species and may be one of the first indicators of faunal change in the intertidal on the southern GBR.

The broad latitudinal distribution of many invertebrates along the GBR indicates that they can reproduce across a range of temperatures, including those at the northern and southern margins of the GBR. Range extensions of species southward along the GBR and changes in reproductive timing as a phenotypic response are likely to occur in response to climate change[203,28]. The southern GBR may therefore function as a refuge of biodiversity if reproductive and recruitment failure occurs in a warmer northern GBR.

Species that now inhabit the GBR and breed successfully at their southern limits in subtropical or temperate waters are probably able to extend their range further south with increasing water temperature, subject to appropriate habitat. Such frontier species may be best adapted to temperature changes associated with global climate change. As they already occur in limited numbers in cooler waters, range shifts would probably be relatively rapid, with southern populations increasing and northern populations decreasing. Some invasive species seem to have the adaptive capacity to cope with increasing temperatures. Fields et al.[86] found that invasive species of *Mytilus* were better adapted than native species to increases in changes in temperature with regards to their physiology.

Southern extension of species will depend on available substrate. Those species associated with coral substrates may be limited in their ability to move southwards, whereas benthic invertebrates occurring on inter-reef areas are less likely to be limited by substrate availability. For many groups such as polychaetes (Hutchings unpublished data), molluscs (W Ponder pers comm) and probably Crustacea (Ahyong unpublished data), a greater diversity occurs in coral rubble and soft sediments than associated with live coral substrates. Therefore, while loss of coral through regular bleaching events would change the community, it might not appreciably impact the overall diversity of these groups. In contrast, many species of soft corals have very specific habitat requirements such as light availability, wave and flow exposure, steepness of the reef slope and sedimentation rates[80]. Suitable substrate for new recruits are generally more limited for soft corals, so their ability to move south will be determined by the availability of hard substrates, which are somewhat lacking south of the current boundaries of the GBR.

### *11.2.4.2 Sea level rise*

Mobile species can migrate landwards if suitable habitats are available, but sedentary species can only migrate through successful larval recruitment to newly established marine habitats (for further comments see chapters 8, 9 and 20).

### *11.2.4.3 Light spectra*

Some tropical marine ecosystems seem to have marginal capacity to cope with turbid conditions, periodic storms and sedimentation that increase light attenuation as confirmed by recent observations[165,207] and examination of the fossil record[241]. On the GBR, benthic invertebrates with photosymbionts already at their range limits may become locally extinct with increased turbidity and sedimentation. The severity of the response may depend on the animal's reliance on its photosymbionts. For example, if the animal can obtain sufficient nutrients directly from feeding during periods of turbidity and sedimentation, the lack of light may cause few problems, and increased suspended organic particles may even contribute significantly to nutrition[8]. However, if the animal depends heavily on its photosymbionts for nutrients, periods of turbidity may be fatal.

### 11.2.4.4 Ocean circulation, ocean acidification, physical disturbance, rainfall and river flood plumes

Some species may benefit from ocean circulation changes through recruitment, providing such changes increase favourable conditions for larvae. For example, populations of the seashell *Strombus luhuanus* on the GBR showed consistently high recruitment for two years following ENSO events, likely due to ocean circulation changes and upwelling of nutrient-rich waters[46].

In the fossil record there are many examples of dramatic changes in faunal composition following major shifts in circulation, the formation of the circumpolar current[242] and the Gulf Stream being two key examples. With these major changes in circulation and associated temperature changes, faunal composition changed completely, suggesting little or no adaptive capacity when changes are massive. However, smaller changes at temperate latitudes during the Pleistocene suggest that some adaptation is possible[121,153]. Clearly, the rate and magnitude of change will determine whether the fauna can adapt.

If changes are short-term and intermittent, adults may be able to survive periods of limited food supply by absorbing body tissue and stopping or reducing reproduction (eg sea urchins[38,30]). Some larvae have the ability to delay settlement until a suitable substrate is found (eg crustaceans[205] and molluscs[97,231], but this comes at the cost of reduced growth or prolonged time in vulnerable larval stages[42,97,231].

The capacity of most benthic invertebrates to adapt to increased storm activity is probably limited. One area worthy of further investigation is morphological plasticity - perhaps growth forms of sedentary or colonial species may be able to change. Various coral species exhibit different degrees of arborescence according to habitat and many nephtheid species (octocorals) prevent tear damage during storms by temporarily contracting their colonies[80].

There is likely to be no short-term capacity for marine invertebrates to adapt to changing rainfall and river flood plumes, given their limited ability to osmoregulate.

The impact of ocean acidification on calcifying marine invertebrates will depend on species' adaptability and there are few experimental data on this. The genetic control of skeleton formation in marine invertebrates is precise and the physiological processes involved are complex. Skeleton formation is similar among the echinoderm classes that diverged over 500 million years ago. This indicates that these and other calcifying benthic invertebrates will have limited capacity to adapt their skeleton forming mechanisms in response to the comparatively rapid changes expected in ocean pH. The decrease in pH of sea water will be greatest in shallow water and so populations of some species living at greater depth may be less affected by ocean acidification.

A multitude of factors contribute to the effect of changes in ocean circulation on marine invertebrate distributions (eg organismal biology and life history, flow fields, coastline topography, habitat and settlement preferences, and the physics of transport) so predictions about outcomes of such circulation changes are difficult. However, some results suggest that simple, common flow fields, which are often observed in association with biogeographic boundaries worldwide, might potentially constrain the geographic range of a species, even when suitable habitat outside that range is abundant. Such boundaries can function as barriers to dispersal and range expansion, with their permeability critically depending on the species' life history and temporal variability in the nearshore flow field[96].

## 11.2.5 Vulnerability and thresholds

### 11.2.5.1 Ocean circulation

Larvae dispersed to unsuitable habitats will die, as will adults unable to feed effectively. Obviously, larvae of species dependent on coral substrate for settlement may be highly vulnerable, especially southern populations due to limited areas of reef south of the GBR[115,116]. Species colonising inter-reef habitats may have more opportunities to settle outside of the GBR, because of the more 'generalised' habitat. Extensive studies have shown the importance of substrate for marine invertebrate settlement[51,174,98,104].

### 11.2.5.2 Water temperature

Distribution changes in direction and magnitude are largely unknown and difficult to predict for benthic invertebrates. However, inshore communities may be more at risk than those offshore, and species already at their temperature limits are most at risk. These species may be able to move south as frontier species, but this depends on the availability of suitable habitat. The fossil record indicates that migratory response to changing temperature is species-specific[1,17,264]. For example, as a result of climate change during the late Quaternary, the bivalve *Venericardia* procera migrated northwards in the Atlantic while the gastropod *Tegula atra* became locally extinct[1].

Life-history strategies will likely play an important role in the ability of a species to migrate in response to changes in water temperature. In sponges, life-history strategies vary considerably across different taxa, with exact details frequently unknown[179]. External gamete production is often highly synchronous and putatively controlled by diverse exogenous and endogenous events, often shortly before the peak summer temperature is reached[89]. Sponges with brooded larvae, especially in sub-littoral and intertidal species, may release gametes continuously throughout the year, while others release in one or two peaks, usually during the warm season. The duration of the reproductive period may also be controlled by environmental factors such as water temperature, and significant inter-population differences in timing have been observed[179]. Another factor that may be important is whether species with short life cycles can adapt better than longer-lived species, especially if temperature increases are rapid. Perhaps some insight could be obtained by examining invasive or 'weed' species that can build up large populations rapidly[178].

Temperature and developmental rates positively correlate in many marine invertebrates[195]. Any increase in temperature will likely cause higher growth rates in embryos, larvae and juveniles, although such change would vary according to temperature change, spawning behaviour and species. However, other abiotic factors may interact with temperature to stunt development[125,218], highlighting the need to consider other potential variables associated with global or local change.

In adults, temperature may not always significantly affect growth. In a survey of molluscs at Heron Island, Frank[88] found that shell growth and temperature were not related within a single population. However, shell growth preceded reproduction in some species[88], so temperature may indirectly affect adult growth by affecting the timing of reproduction.

Many invertebrates, including echinoderms and polychaetes, are known to participate in mass spawning of corals[12]. This annual event is controlled by lunar cues and is potentially fine-tuned by water temperature. Lunar cues are likely to initiate this reproductive event, regardless of sea temperature change. However, too little is known about the influence of temperature to make useful predictions. On the southern GBR, echinoderms also spawn around the time that corals release. Hypotheses explain the evolution of mass spawning among different species. Firstly, there is a relationship between mass spawning and temperature differential. Mass spawning occurs in regions where there is a greater difference in seasonal temperatures. On the GBR, where thermal conditions fluctuate seasonally, this results in species taking advantage of optimal conditions. Mass spawning swamp predators and increases the survivorship potential of each species[12]. Ultimately, it is unknown why species on the GBR spawn synchronously, but climate change may nevertheless interfere directly or indirectly with current spawning patterns. Climate change may also affect fecundity and body size, but there are currently limited data available for non-coral benthic marine invertebrates.

Marine intertidal molluscs, such as oysters, are exposed to multiple stressors in estuaries, including varying environmental temperature and levels of trace metals that may interactively affect their physiology. Exacerbation of cadmium effects by elevated temperature suggests that oyster populations subjected to elevated temperature may become more susceptible to trace metal pollution[258]. This is an important issue given the increasing human population along the Queensland coast and potential consequences for the aquaculture industry.

#### *11.2.5.3 Ocean acidification*

Any reductions in densities of coral skeletons will impact on the boring and cryptofaunal communities present within live and dead coral[138]. Similarly, changes to encrusting communities have the potential to modify the suite of benthic invertebrates that are associated with such communities. For many benthic invertebrates the most vulnerable life stage is their pelagic larva. The threshold tolerance for survival in reduced pH conditions are known for few taxa[162,250] and is an area identified for focused research[159].

#### *11.2.5.4 Other light spectra, sea level rise, physical disturbance, rainfall and river flood plumes*

Species with resident zooxanthellae are likely to be most vulnerable, as sea level rise, rainfall and physical disturbance associated with turbidity and sedimentation increase light attenuation and affect rates of photosynthesis in symbionts[75] (see section 11.2.3.4). Changes in algal distribution and loss of live coral colonies will impact on herbivores and those associated with living coral colonies, such as obligate symbionts (eg hapalogastrid and trapeziid crabs[45]).

The vulnerability of invertebrates to sea level rise will largely be determined by the speed and magnitude of sea level rise. Vertical accretion rates of coral reefs are not predicted to be sufficient to keep up with an estimated sea level rise of 15 mm per year (eg Buddemeier and Smith[32]). However, the fossil record shows that some Pacific coral reefs (eg the Huon Peninsula, Papua New Guinea, kept pace with sea level changes during the Younger Dryas Event at the end of the last glacial maximum (approximately 11,000 years before present), when sea level rose by 50 metres over about 5,000 years (a rate of 10 mm per year)[48]. During the same period the growth on the GBR often lagged behind[67]. Evidence from a Triassic reef in the Austrian Alps, however, suggests that the observed three well-defined reef growth stages were not only affected by small-scale sea level fluctuations, but also by storm damage and increased sedimentation input[20].

Intertidal and shallow water species are most vulnerable to increased storm activity. Increased river flow and sedimentation will most severely impact sessile or infaunal species that cannot avoid the disturbance. They will be buried, torn from the substrate or washed away. In any case, they are unlikely to be able to reburrow or reattach themselves to the substrate and will most likely perish. The success of settlement or resettlement is inversely correlated with sediment depth, and there is a general trend of shifting community structure observed for sponges based on increasing sedimentation and resuspension[16,298,44] (see section 11.2.1.4).

Fringing reefs can effectively buffer wave action, but loss of reef framework already weakened by bioerosion, is far more susceptible to breakage during storms, which leads to increased erosion of beaches and coastal structures[143]. Significant differences in bioeroding communities, strongly influenced by water quality, are present both within and between reefs and across the shelf, at least in the northern GBR[199]. Coral substrate with boring communities dominated by boring sponges may be more flexible and better able to withstand the shearing forces of storms than communities dominated by other borers.

The timing of fresh water inputs is critical. Larvae may be far more susceptible to surface plumes than adults, so fresh water influxes during reproductive periods may have a greater impact than at other times (Przeslawski[216] and literature cited therein). This is particularly important for species that die after spawning because it may lead to loss of an entire season's recruitment.

All the above factors will act synergistically, and the impact on benthic invertebrates will vary according to existing natural and anthropogenic stressors (eg ultraviolet radiation, overfishing and terrestrial runoff) and the rates of environmental change.

## 11.3 Linkages with other ecosystem components

The vertical linkages that exist in lagoon systems on the GBR are detritus driven with tight nutrient cycling. One of the most important sources of detritus is coral mucous. If the linkage between coral and soft-sediment communities is lost with a reduction in productivity, the abundance of benthic species will decrease. In addition, changes in benthic-pelagic coupling may have detrimental effects on both benthic and planktonic invertebrates (eg diurnal migration of crustaceans; McKinnon et al. chapter 6, Kingsford and Welch chapter 18).

Horizontal linkages exist between reefs and soft-sediments, including seagrass beds and mangroves (Waycott et al. chapter 8 and Lovelock and Ellison chapter 9). For example, penaeid prawns support a multi-million dollar fishery off the coast of eastern Queensland. Penaeids are typically trawled from nearshore and inter-reef areas. Larvae of most commercial penaeids in GBR waters require nearshore or estuarine seagrass habitats for settlement and growth to maturity, and consequently are highly susceptible to loss of seagrass. Some species, such as the banana prawn (*Fenneropenaeus merguiensis*) and giant tiger prawn (*Penaeus monodon*), favour turbid inshore habitats[105,106]. In other species, such as the red-spot king prawn (*Melicertus longistylus*), juveniles use the reef flat as a nursery area, and adults occupy the adjacent lagoon and inter-reef carbonate sediments[72,107]. Juveniles of most species of commercial penaeid, however, 'grow out' in estuaries and nearshore seagrass beds, and migrate to offshore lagoon and inter-reef waters. Similarly, commercial crab species, such as the blue swimming crab (*Portunus pelagicus*) and mud crab (*Scylla serrata*), are tied to seagrass beds as juveniles and move into deeper water as adults, with the latter species migrating offshore. Any factors that reduce the extent or quality of seagrass habitats could negatively impact prawn and crab populations, and the productivity of the fishery. For example, seasonal reductions in salinity and increased turbidity associated with high summer rainfall appear to be a primary determinant of seagrass species distribution[29,60]. Moreover, increased nutrient loads from terrestrial runoff are known to be detrimental to penaeid larvae[187,271]. High summer river flows are linked to higher productivity of several fisheries, partly through the stimulating downstream movement of individuals and partly through stimulating growth rates and survivorship through increased primary productivity. High summer flows are important for emigration of juvenile prawns and sub-adults to near- and offshore habitats, and may further stimulate production through increased food availability[170]. Despite the complex interactions of changing environmental parameters, changes in rainfall patterns and freshwater input will directly impact seagrass communities (Waycott et al. chapter 8). Obviously, the net impact will depend on the magnitude and direction of changes in environmental parameters.

Benthic invertebrates are an important food source for many animals higher in the food chain such as fish, marine turtles and permanent and migratory birds. Therefore, reduction or loss of these invertebrate communities can have severe effects at higher trophic levels.

### 11.3.1 Constraints to adaptation

Lagoon and subtidal species may be more vulnerable to changing conditions than intertidal species because they presumably have not evolved the same level of protective functions to dynamic and stressful conditions. For example, interspecific comparisons of turban snails revealed that an intertidal species had more effective heat-shock responses than a subtidal species[270,269]. However, the degree of generality of this observation is unknown. At least among polychaetes and crustaceans, many intertidal species also occur in shallow subtidal habitats, suggesting no difference in ability to respond to stressful conditions.

### 11.3.2 Interactions between stressors

The most tangible and visible impact of climate change on the GBR to date has been mass coral bleaching. This undoubtedly has had a major impact on obligate associates of corals and the non-coral benthos (eg lower food availability and habitat loss). Surprisingly, the impact of coral bleaching on these organisms has not yet been monitored on the GBR.

Among benthic invertebrates, interactions between environmental factors may play a particularly important role in assessing climate change impacts. Benthic invertebrates are often sessile (eg sponges and bryozoans), slow moving (eg many echinoderms and gastropods) or infaunal, and are therefore restricted in their ability to escape unfavourable conditions that may amplify the negative effects of stressors associated with climate change.

Many studies examining the impacts of climate change focus on single factors, and these may falsely suggest that increased temperature, current changes, varying precipitation or other stressors associated with climate change will not significantly affect an organism. Whereas a single factor considered in isolation may have a negligible overall effect, the combined impact of multiple factors may be significant. For example, a single-factor study examining the effects of UVR on marine invertebrate development suggested that molluscan embryos of *Siphonaria denticulata* and *Bembicium nanum* were invulnerable to natural intensities of UVR[218]. Subsequent multifactor experiments revealed that these 'invulnerable' embryos are in fact susceptible to the negative effects of UVR when exposed to synchronous stressors, including those associated with climate change such as temperature, salinity and desiccation[217]. Interactions between abiotic and biotic factors may also affect larval settlement and behaviour, directly affecting community composition and structure. Settlement cues for marine invertebrate larvae probably involve multiple factors[156,282], including temperature and salinity[266], each of which will be modified by global climate change.

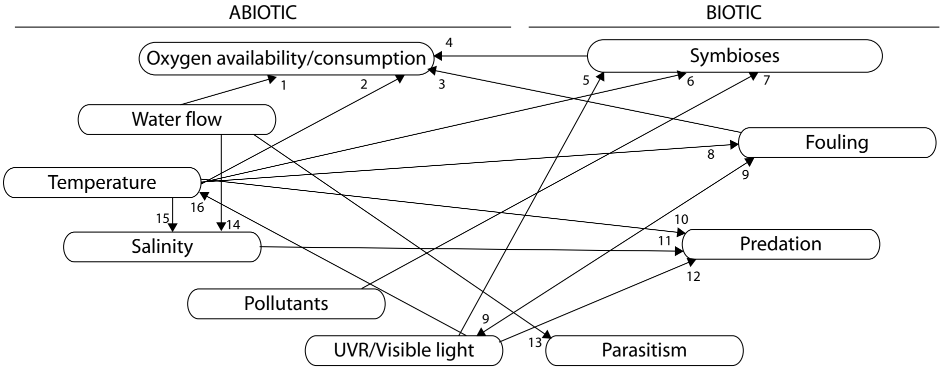
The invasive ability of marine invertebrates should also be considered in a multifactor context[234]. Single-factor studies are relatively simple with easily interpreted results, but they may underestimate 'real-world' effects. Such studies are most appropriate as a baseline or platform for further multifactor research. Some data suggest that impacted communities are more susceptible to invasion by introduced species[59]. However, as most introduced species arrive in estuaries and tend to remain there, it is difficult to know if impacted reef environments are susceptible to these invaders.

Multifactor experiments are even more important when the relationships between potential stressors are considered. Climate change will involve multiple abiotic factors such as fresh water input (salinity) and temperature, and these factors will in turn affect other abiotic and biotic stressors such as oxygen availability and parasitism. This forms a complex web of potential interactions (Figure 11.2). To further complicate matters, the interactive effects of many stressors, including those associated with climate change, are complex[125] and have both acute and chronic effects[256]. Some stressors may even have different effects on the same species, depending on the history of the assemblage or environment[135]. Thus, to avoid oversimplification, generalisations concerning interactive effects of abiotic and biotic factors should be made cautiously and only when numerous species have been examined. The use of multifactor experiments to study impacts of climate change at appropriate temporal, taxonomic, and spatial scales represents a significant challenge to ecologists but is crucial to provide an ecologically realistic assessment.

### 11.3.3 Threats to resilience

As stated previously, the response of marine benthic communities to climate change is difficult to assess because of the lack of knowledge about basic distribution and ecology for most species.

***Figure 11.2*** *Interactions of abiotic and biotic variables that can affect benthic invertebrates (adapted from Przeslawski[216]). Variables listed do not include events associated with them (eg flooding, runoff and storms), rather only the specific stressors are included*[e]



e.g.
1 Finellei et al 2006
2 Roberts & McMinn 2004
3 Cohen & Strathmann 1996
4 Peyton et al 2004
5 Verde & McCloskey 2002
6 Second & Augustine 2000
7 Webster et al 2001
8 Lambert & Lambert 2003
9 Biermann et al 1992
10 Sanford 1999
11 Ma & Purcell 2005
12 Williamson et al 1999
13 Lenniham et al 1999
14 Gillanders & Kingsford 2002
15 Przeslawski 2005
16 Wissman 2003

Similarly, resilience to these impacts is largely unknown. While the ecosystem may be able to recover from single events, we believe the potential for recovery from multiple stressors or recurrent events expected from climate change would be significantly reduced. Such a situation is being observed with coral communities that have been bleached several times. These reefs do not recover to pre-bleached conditions[124] before being subjected to another bleaching event, supporting the contention that it is the speed, frequency and magnitude of change that are the major threats.

## 11.4 Summary and recommendations

### 11.4.1 Major vulnerabilities to climate change

Species that depend on coral reef substrate will have reduced success with loss of coral communities and increased rates of bioerosion, leading to reduction of available reef substrates (Hoegh-Guldberg et al. chapter 10, Fabricius et al. chapter 17) (Figure 11.3). In contrast, faunas associated with soft bottoms, including those in inter-reef/shelf habitats or small coral isolates, will primarily be affected by changes in temperature (Figure 11.4) and may be able to survive either by moving into deeper, cooler water or into higher latitudes. Intertidal communities, including coastal/estuarine communities, will be impacted by physical loss of habitat in some areas as a result of sea level rise and more frequent storm events, but perhaps also with expansion of habitat in other areas (Sheaves et al. chapter 19) (Figure 11.5). Communities will be impacted by increased air and ocean temperatures, as well as changes in rainfall patterns.

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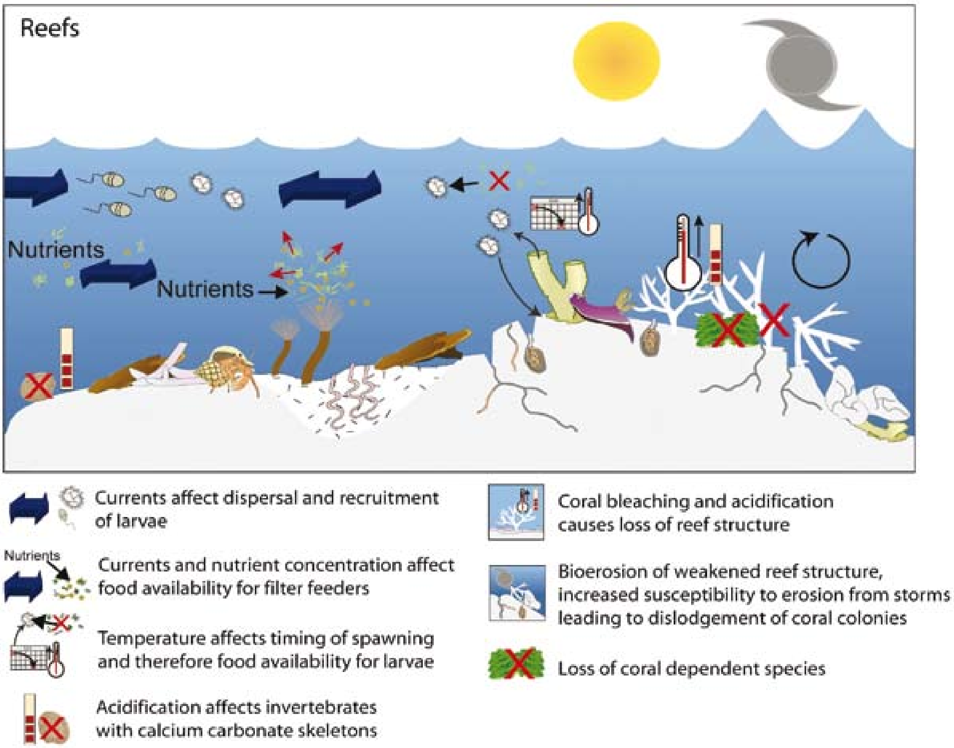
[e] This list is by no means comprehensive, but instead illustrates the relationships between potential stressors. The relationships illustrated are not ubiquitous or exhaustive, rather, each arrow represents a potential relationship that has been identified in at least one study. A single arrow indicates a relationship in which one variable affects the other. A double arrow indicates a relationship in which both variables affect each other.

***Figure 11.3*** *Main climate change drivers that may affect benthic invertebrates living on reefs*

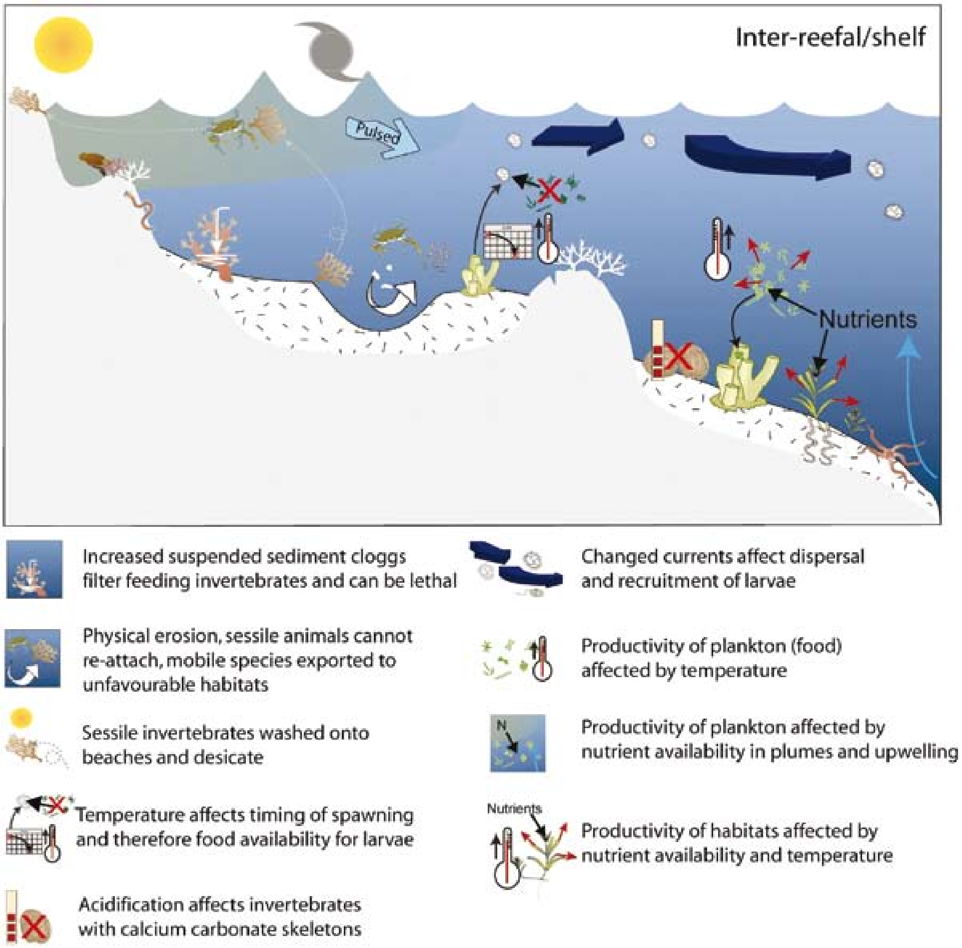


### *11.4.1.1 Extinctions and change of reef framework*

Some populations of invertebrates, particularly those in the northern GBR, may be vulnerable to extinction due to their inability to respond phenotypically to the pace of environmental change. This may be a widespread phenomenon given that the entire Indo–Pacific will be subjected to similar warming as the northern GBR, although populations currently in the cooler part of their ranges may survive. Local extinction risk has been highlighted in terrestrial models with extinction rates between 15 and 37 percent predicted for mid-range climate change scenarios[267]. A decline in invertebrate community diversity in response to ocean warming has already been documented for intertidal habitats in North America[240,254], but similar studies have yet to be conducted on the GBR. Similarly, the studies of Tomanek[269] and Sorte and Hofmann[261] have found that the gastropod *Nucella caniculata* is more stressed at its range edges, supporting the suggestion that many intertidal invertebrates may be at the limit of their ability to adapt, even to a small increase in temperature[269]. Much remains to be investigated as to the ability of invertebrates to adapt to higher temperatures.

During the Pleistocene era, sea level rise combined with increased water temperature may have contributed to periods of extinction[17]. However, Indo–West Pacific coral and mollusc species had a lower rate of extinction then their Caribbean counterparts[256], suggesting that this region may be less vulnerable to species extinction than other tropical regions. Furthermore, although coral reef

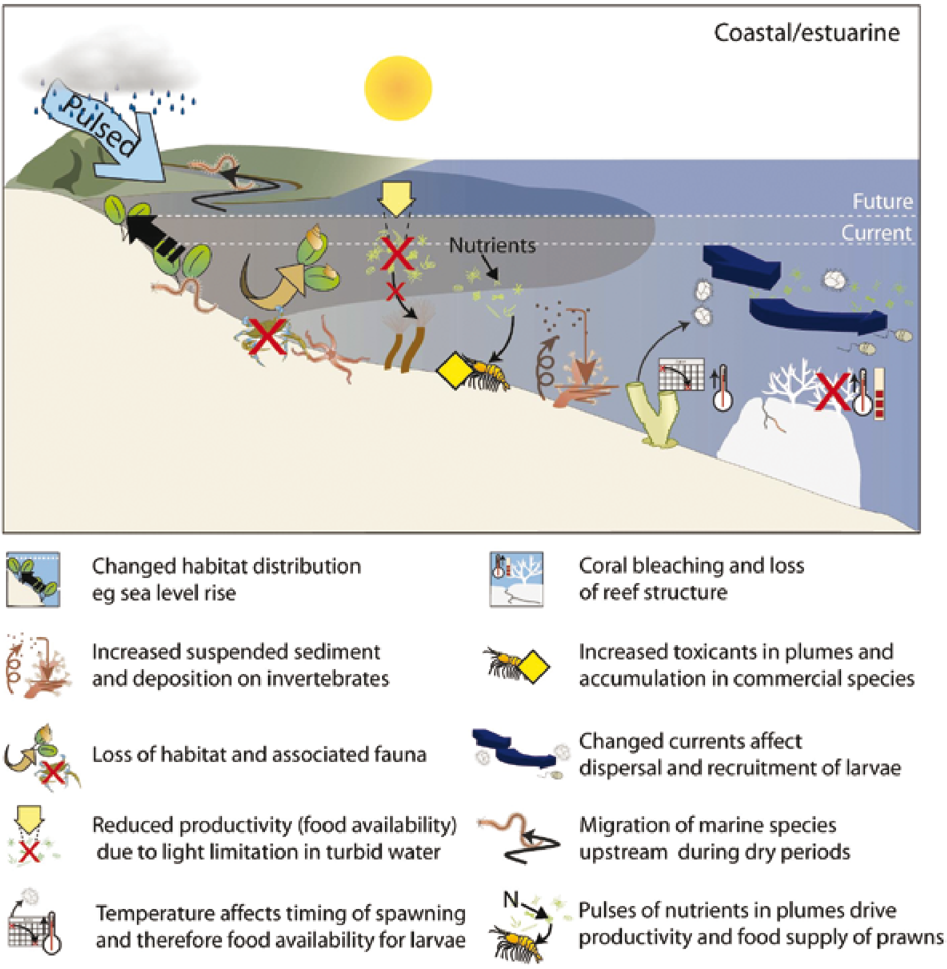
***Figure 11.4*** *Main climate change drivers that may affect benthic invertebrates of inter-reef/shelf habitats*



communities in the Pacific changed during these periods of sea level rise, there was little evidence of large-scale or permanent loss of overall diversity[256].

Compared to other tropical marine ecosystems in the Indo–West Pacific, there are relatively few narrow-range endemics on the GBR, and the risk of complete extinction may be comparatively low overall. There are exceptions, however, including narrow-range endemic sea stars on the Queensland coast and GBR islands[62,37]. Partial and local extinctions are a risk, perhaps particularly in the case of coastal species. Hooper and Kennedy[129] and Hooper and Ekins[128] report between 50 and 70 percent of sponge species from subtropical and tropical waters, respectively, are known only from single specimens. Thus, significant proportions of genetic diversity are at risk through small-scale regional extinctions driven by climate change.

***Figure* 11.5** *Main climate change drivers that may affect benthic invertebrates living in coastal and estuarine habitats of the GBR*



Increased rates of coral death following bleaching and other physiological stresses result in increased rates of bioerosion leading to loss of reef framework[202]. If scleractinian corals do not readily adapt to rising sea surface temperatures and if frequency of bleaching events increases, increasing proportions of structural elements of the reef that would normally be quickly recolonised (eg coral skeletons) remain barren for longer periods. As a result, it is expected that abundance and density of bioeroding sponges (primarily the families Clionaidae, Spirastrellidae and Alectonidae) will increase and further weaken the structural framework of the reef[239]. With an additional expected increase in tropical cyclone intensity and frequency, complete destruction of large reef areas, especially the more exposed parts, is likely.

Marine benthic invertebrates are not only vulnerable to extinction from overwhelming environmental stressors, but from loss of habitat. Those particularly vulnerable are obligate associates of live corals, including molluscs (both gastropods and some bivalves)[232], hapalocarcinid and trapeziid crabs[45], polychaete worms[255] and coral-associated barnacles[6]. Similarly, many sponges are niche specialists on reefs, found only in particular habitats such as in caves, overhangs and coral interstices[127], such that degradation or destruction of niches will impact on the constituent species. Crinoids are a diverse assemblage of coral reef specialists[78,39] that depend on live coral reef habitat and are depleted when corals are impacted by crown-of-thorns starfish[78].

### 11.4.1.2 Range extensions of keystone species

Range extensions of keystone species can have a disproportionate effect on community structure. A recent example is the range extension of the sea urchin *Centrostephanus rodgersii* into Tasmania, likely due to changes in current flow associated with climate change[7]. In Tasmania this urchin has contributed to a phase shift from a kelp-dominated community to a barren seascape[7]. Another example is the recent invasion of the clam *Potamocorbula amurensis* in San Francisco Bay. This species has greatly contributed to the regional $CO_2$ source through its respiration and calcification, with associated implications for ocean acidification[50]. With range shifts of keystone species, the GBR may be similarly vulnerable to invasive species, particularly if invasive species are able to recruit earlier than native species[262].

The corallivorous crown-of-thorns starfish, *Acanthaster planci*, has caused well-documented and widespread damage to many coral reefs in the Indo–Pacific over the past four decades[23]. Crown-of thorns starfish generally occur in low densities on the GBR, but periodically appear in large numbers. These cycles on the GBR have occurred from 1962 to1976, 1979 to 1991 and 1993 to the present[31]. The outbreak ends when coral prey is exhausted. Reef recovery following intense predation by the starfish is variable, with some reefs not recovering for 10 to15 years[61]. The starfish, while reasonably common in the southern GBR, does not appear to exhibit the characteristic outbreak cycle in the south that it does in the north, although there was a major outbreak at Elizabeth and Middleton reefs in the mid-1980s[139]. It is likely that sea temperature has a major influence on the timing of spawning and on the larval performance in this species. There is potential that populations of the starfish may become larger in the south, facilitated by increased temperatures associated with climate change. If this temperature rise is accompanied by increased intensity flood plumes and associated nutrients, as is predicted, then plagues are likely to become more common in the southern GBR. There is good evidence that plagues are facilitated by eutrophic terrestrial runoff[21,31].

Many invertebrates on the GBR have a wide latitudinal distribution, and it is likely that reproduction varies markedly between the northern and the southern regions, as shown for corals. For example, the echinoderm *Ophiocoma dentata* spawns at the same time as the corals (November to December) on the northern GBR, but in summer and winter on the southern GBR (Byrne unpublished data). The generality of this phenomenon on the GBR is unknown.

### 11.4.1.3 Community structure

As already mentioned, range extensions of keystone species can affect community structure[7]. Community structure can also be dramatically altered by changes in substrate. Modeling of bleaching events on coral reefs and rates of recovery clearly show that the persistence of hard corals will depend

in part on the factors that constrain excessive algal biomass[295]. If the proportion of algae cover on the reef increases – as is already occurring on inshore reefs – this will modify the ability of non-corals to recruit to the reef. Relatively few species of molluscs[232] and polychaetes[138] are associated with live corals as opposed to soft sediments or coral rubble. However, changes from living coral substrate to dead coral or algae would change these communities dramatically[302], not only for the molluscs and polychaetes, but also for all other groups that are found predominantly on or in living corals. Following from this scenario, increasing algal proliferation would lead to a higher abundance of grazers (eg echinoids, gastropods and chitons), followed by excessive bioerosion and loss of reef framework and biodiversity[202].

### 11.4.2 Potential management responses

Multi-scale approaches may provide suitable management strategies for benthic invertebrates of the GBR. This approach is advocated by Chabanet et al.[47] to quantify anthropogenic disturbance at various scales on tropical reefs, but could be modified to quantify effects of various stressors associated with both climate change and direct anthropogenic disturbance. Climate change can be viewed as a series of disturbances, some continuous (eg ocean temperature and acidification) and some stochastic (eg storms and flooding). A multi-scale approach to climate change on the GBR may allow comparison and impact assessment over a range of scales, which is particularly suited to the spatial heterogeneity, diversity of life histories and substrate-specificity of benthic invertebrates.

Building resilience to climate change impacts could be achieved by reducing the impact of other anthropogenic stressors such as eutrophication from land runoff, trawling, recreational fishing and tourism.

Education of the public to engender stewardship and community awareness of benthic invertebrates and their critical role in GBR ecosystem health will be important to the success of protective management strategies.

Marine invertebrate conservation strategies on the GBR should recognise the possibility of locally unique bioactives and intraspecific genetic variation that may be important to the success of species, including widespread species.

### 11.4.3 Recommendation for future studies

Given the short time available it is imperative that future studies to assess the impacts of climate change are clearly targeted. We suggest that the primary purposes of these studies as related to benthic invertebrates should be to:

- detect change
- implement management strategies
- attempt to stop or reduce predicted impacts.

Targeted surveys should be undertaken for a limited number of invertebrate species, which should be selected to encompass the range of reproductive strategies found in invertebrates, including both sexual and asexual reproduction, brooders and free-spawners, and species with long- and short-lived larvae. These species should also exhibit a range of distributions along the GBR, from widely distributed Indo–Pacific species, to ones restricted to particular regions of the GBR and narrow range endemics. In addition, targeted species should exhibit a range of life styles and occupy varying habitats both on reefs and in inter-reef areas. Species selected should be taxonomically well known and easy to identify by non-specialists with limited training (a small workshop of invertebrate biologists could develop such a list of target species). The selected taxa should be sampled seasonally to document changes in density, timing of spawning, reproductive success, size and community interactions. In addition, both commercially and non-commercially important species should be targeted. By sampling along the GBR, regional differences should be detected. The surveys must use statistically valid sampling techniques to ensure that the results are robust.

The data from these targeted surveys will highlight the types of species that are most impacted, as well as the regions of the reef where maximum impact is occurring. Combining this data with concurrently measured physical data, it may be possible to identify other factors that are contributing to these highly impacted sites, such as excessive trawling causing increased suspended matter in the water column, high nutrient levels from land runoff, high tourist activity, etc. The impact of these factors can then be modified by management strategies.

To accurately assess the impacts of climate change and implement appropriate conservation management strategies, a measure of stress on GBR organisms is required before they will show visible sub-lethal effects. Biochemical measurements of stress seem the most promising method, including quantification of heat-shock proteins and thermal acclimation, DNA repair rates and antioxidant measurements. Benthic invertebrates are ideal for these studies[269]. They are relatively easy to collect, monitor and culture in the laboratory; represent a huge range of phyla, habitats and life histories for comparative analyses; and include genera in which similar work has already been conducted in other regions (eg *Nucella*[261] and *Tegula*[269]).

The results of these studies will need to be published in recognised scientific journals, but precise summaries in plain English also need to be made available to the general public through the media. Only then is it likely that there will be enough political will to implement actions to either stop or reduce the impacts.

Finally, given the high profile of the GBRMPA, these results and strategies should then be made available worldwide for other managers of tropical marine ecosystems to implement.

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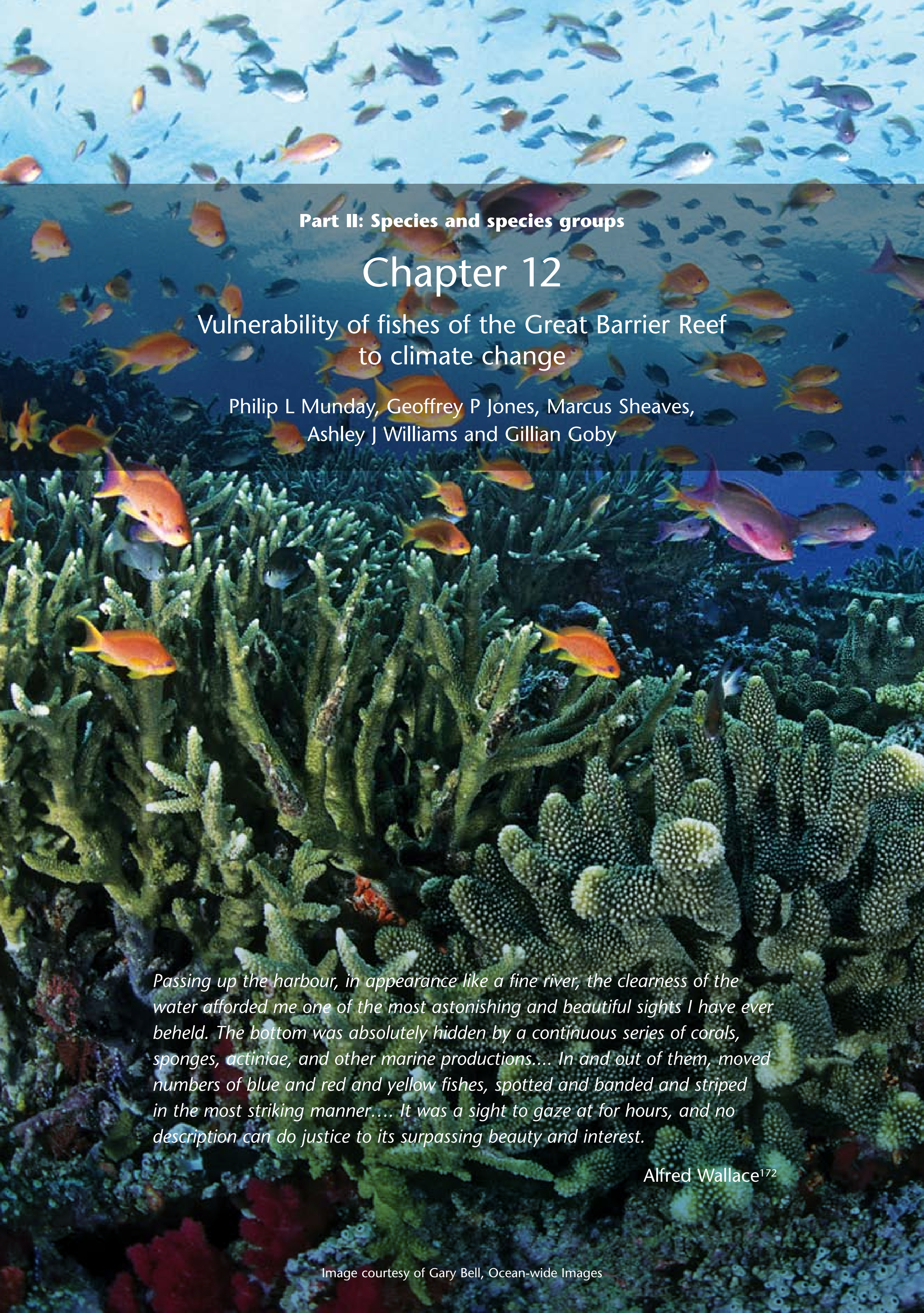


## Part II: Species and species groups

# Chapter 12

# Vulnerability of fishes of the Great Barrier Reef to climate change

Philip L Munday, Geoffrey P Jones, Marcus Sheaves,
Ashley J Williams and Gillian Goby

> *Passing up the harbour, in appearance like a fine river, the clearness of the water afforded me one of the most astonishing and beautiful sights I have ever beheld. The bottom was absolutely hidden by a continuous series of corals, sponges, actiniae, and other marine productions.... In and out of them, moved numbers of blue and red and yellow fishes, spotted and banded and striped in the most striking manner.... It was a sight to gaze at for hours, and no description can do justice to its surpassing beauty and interest.*
>
> Alfred Wallace[172]

Image courtesy of Gary Bell, Ocean-wide Images

## 12.1 Introduction

Climate change has already caused significant impacts to Earth's ecosystems. Shifts in plant and animal biogeographic ranges[125], changes to population abundance[74,173], adjustments in the timing of seasonal activities[74,144,171] and the establishment of invasive species[173] have all been attributed to climate change. Most examples of biological impacts from climate change involve terrestrial species, however, similar effects have been observed in marine species, especially from temperate regions[5,165,55,162,63]. The impact of climate change on coral reefs has also been widely considered, mostly with regard to coral bleaching and the degradation of coral communities[68,75]. Much less attention has been given to the impact that climate change will have on other organisms that are associated with coral reefs. Fish are one of the most conspicuous and diverse components of tropical marine ecosystems, yet how they will be affected by climate change has not been comprehensively assessed[142,114].

### 12.1.1 Fishes of the Great Barrier Reef

Over 1500 species of fish are estimated to occur on the Great Barrier Reef (GBR)[118], ranging from tiny gobies weighing less than a gram and living just a few months[43], to giant groupers weighing many hundreds of kilograms and living decades[137,126]. Most fish species found on the GBR are widespread in the tropical western Pacific, and many have distributions that extend into the Indian Ocean and central Pacific[137]. This means that the fish fauna of the GBR has strong affinities with neighbouring regions, such as tropical Western Australia, south-east Asia and the islands of the western and central Pacific.

The GBR is a complex network of different habitats for fishes, including shallow coastal and estuarine waters, coral reefs, a variety of inter-reef environments, and the continental slope with accompanying deepwater pelagic zone. Each of these broad habitat types contains a characteristic suite of species. The vast majority of GBR fish species occur on coral reefs. A smaller number of species occupy coastal waters and inter-reef areas, while others are more mobile and inhabit the pelagic zone around reefs. Characteristic fishes of coral reefs include the butterflyfishes (family: Chaetodontidae), angelfishes (Pomacanthidae), wrasses (Labridae), parrotfishes (Scaridae), damselfishes (Pomacentridae) and surgeonfishes (Acanthuridae)[32]. In terms of species diversity, coral reef fish assemblages are dominated by wrasses (Labridae), damselfishes (Pomacentridae), gobies (Gobiidae) cardinalfishes (Apogonidae), groupers (Serranidae) and blennies (Blennidae). Although some coral reef fishes can reach large sizes (greater than 1 metre), the vast majority of species are relatively small and many are less than 100 mm in length[115].

A diverse range of taxa, including emperors (Lethrinidae), snappers (Lutjanidae), coral breams (Nemipteridae), goatfishes (Mullidae), grunters (Teraponidae), and puffers (Tetraodontidae) occur on the soft sediment and hard-bottom areas between reefs[174,29]. Trevallies (Carangidae), tunas and mackerels (Scombridae) are common in the pelagic zone around reefs.

There is considerable structure in the spatial distribution of fishes within the GBR. Most strikingly, the relative abundance of many species changes dramatically between inshore, mid-shelf and outer-shelf reefs[181,146,179]. Some species are most abundant on inshore reefs, whereas other species are more abundant on mid- or outer-shelf reefs. Differences in habitat type, food supply and physical conditions across the shelf are likely to be responsible for this distinct cross-shelf pattern of community structure. The distribution of species also changes along the length of the GBR, although the pattern is not

as distinct as that observed across the shelf[179]. Finally, the distribution of fishes varies within reefs. Many reef fishes occur in a relatively narrow depth range or are consistently found in a particular reef zone (eg forereef, reef flat, backreef or lagoon)[147,120]. Consequently, despite unpredictable spatial and temporal variation in the abundance of individual species, there are relatively predictable patterns of community structure within reefs, across the continental shelf, and along the length of the GBR.

Fish have a significant presence in all major feeding groups on the GBR – they are herbivores, carnivores, planktivores, omnivores and piscivores. They are the dominant large predators on reefs and are important for energy transfer throughout the reef ecosystem. Some species also have key functional roles[9]. For example, grazing herbivorous fishes consume macroalgae that might otherwise overgrow and smother corals[103,104]. Other species facilitate the settlement of corals and coralline algae by removing sediment and fine algae from the substratum[166,9]. Reef fishes also have high economic value. The diversity and abundance of fishes on the GBR underpins a multi-billion dollar regional tourism industry (A$6.1 billion) and some species support important commercial and recreational fisheries, worth an estimated A$145 million and A$610 million (GDP) respectively per annum[57,1]. Clearly, substantial changes to the distribution or abundance of fishes on the GBR due to climate change could have serious consequences for the ecological function of the GBR and the economies and social well-being of people that depend on it.

### 12.1.2 Critical factors for fish survival

Nearly all GBR fishes have a life cycle that includes a pelagic larval stage, which lasts for a period of weeks to months, depending on the species[97]. For species where adults are also pelagic, larvae can recruit directly into the juvenile population. For most other species, however, the pelagic larvae must transition to a benthic existence to join the juvenile and adult population. When they are sufficiently well developed, larvae metamorphose and settle to the reef[98], often in the same habitat used by juveniles or adults[21]. After settlement, most coral reef fishes are relatively sedentary, although some species move from juvenile to adult habitats as they develop[99]. A few species, such as some snappers and groupers, settle into coastal and estuarine locations and migrate to reefs or deeper inter-reef areas as juveniles or subadults[156].

Climate change will affect populations and communities of fishes on the GBR through a range of impacts on either the larval, juvenile or adult phases. Dispersal and survival patterns of fish larvae play a key role in the dynamics of adult populations[47,45,46] and the ecological and genetic connectivity between populations[152,38]. The larval stage of reef fishes is highly sensitive to environmental conditions[98] and any changes to the growth, survival, or range of larval dispersal patterns brought about by climate change could have significant consequences for the distribution and abundance of adult populations.

The impact of climate change on the structure of coral reef habitats will also have far-reaching consequences for fish populations and communities. Recent episodes of coral bleaching from elevated sea temperatures have seriously degraded reefs around the world[176]. The loss of coral from bleaching has caused significant declines in the diversity and abundance of reef fishes in some places[184,135] and this effect will be magnified if the structural complexity of reefs declines as a result of continued degradation[56]. The amount of suitable habitat for reef fishes will be further compromised if the effects of coral bleaching interact with other disturbances that kill live coral, such as outbreaks of crown of thorns starfish or terrestrial pollution. Although the GBR is currently in relatively good condition, it cannot escape the global affects of climate change. The interacting effects of climate change and other stressors have the potential to substantially alter the structure of fish communities on the GBR.

Here we use available data for temperate and tropical marine fishes to assess and predict the likely impacts of climate change on the life histories, ecology, and distribution of fishes on the GBR. We limit our analysis to teleost fishes (bony fishes); sharks and rays (cartilaginous fishes) are considered in a separate chapter (Chin and Kyne chapter 13). We first examine the exposure and sensitivity of tropical marine fishes to changes in physical and oceanographic conditions predicted to occur due to climate change on the GBR by the end of this century (Lough chapter 2). We then explore the possible impacts that these sensitivities will have on life histories, population dynamics, community structure and geographical distributions of fishes on the GBR. We assess the possible consequences for fisheries and consider how climate change might interact with other human-induced impacts. There is considerable uncertainty about the magnitude and in some cases even the direction, of physical changes that will occur on the GBR because of climate change. These uncertainties mean that our conclusions are tentative and often speculative. Nevertheless, our analysis identifies areas of concern regarding the possible effects of climate change on GBR fishes and critical areas for future management and research.

## 12.2 Vulnerability of fishes to climate change: exposure and sensitivity

### 12.2.1 Changes in water temperature

All species have thermal optima where physiological processes are maximised or operate most effectively. This thermal range of peak performance is narrower than the thermal tolerance limits exhibited by the species and may differ throughout the species geographical distribution due to acclimation or local-adaptation to different temperature regimes[64]. Fishes are ectotherms and temperature has a critical effect on their physiology and whole-organism function. Changes of a few degrees Celsius in ambient temperature can influence physiological condition, developmental rate, growth rate, swimming ability, reproductive performance, and behaviour[185]. Even if coral reef fishes are not living near their upper thermal limits[112], the predicted 1 to 3°C rise in mean sea temperature on the GBR by 2100 (Lough chapter 2) will almost certainly influence their functional capacity, life-histories and behaviour. The magnitude of any effects, however, are difficult to predict because: i) most studies on the effects of temperature on organism function have been conducted on temperate fishes; ii) tropical marine fishes may be more sensitive to elevated temperature than temperate marine fishes, because annual variation in water temperature experienced by tropical species is generally less than that experienced by temperate species; iii) cellular and physiological responses to temperature will interact in complex ways with environmental factors, such as food availability, to determine the outcome of higher temperature on individual phenotypic and life history traits; and iv) there is considerable potential for acclimation and adaptation to changes in temperature.

Fishes are particularly sensitive to temperature during their early life history. Across a range of species, embryonic development rate increases nearly threefold for every 10°C increase in temperature[143]. Therefore, an increase in water temperature of 1 to 3°C on the GBR could shorten the incubation period of eggs for both pelagic and demersal spawning fishes. After hatching, increased temperature tends to increase larval growth rate, decrease the age at metamorphosis, and increase swimming ability[11,76]. In a recent experimental analysis, Green and Fisher[58] showed that larval duration of the anemone fish *Amphiprion melanopus* was 25 percent shorter, growth rate was higher, and swimming ability enhanced at 28°C compared to 25°C. These traits could all potentially improve the survival prospects of larval fish by reducing the time they spend in the pelagic environment and improving their ability to feed and escape predators.

There is increasing evidence that the survival of larval coral reef fishes is linked to growth rate, with individuals from strong recruitment pulses often exhibiting higher growth rates during the larval period than those from weak recruitment pulses[155,12,183]. Several studies have found a positive correlation between larval growth rate and ocean temperature[105,183] and one[110] found that temperature had a much greater influence on larval growth than did food supply. Together, these results suggest that the 1 to 3°C increase in sea temperature predicted for the GBR might not, by itself, be detrimental to the survival of larval fishes.

In general, the growth rate of fishes increases with temperature, up to an optimal temperature, after which it declines rapidly with increasing temperature[82]. However, this deceptively simple relationship is affected by food availability. A positive relationship between growth rate and temperature only occurs if fish are able to increase their food intake at higher temperatures. Growth rate declines with increasing temperature for fishes on a fixed and restricted food ration because the energetic cost of basic metabolic maintenance increases with temperature[82]. This means that any growth advantage from increased temperature could be suppressed if food availability is limited. Of course, growth rate will decline sharply if increasing temperature causes a serious reduction in food availability. For example, slower growth appears to have occurred in three species of herbivorous damselfishes during warm El Niño conditions in the Galápagos Islands[108]. The green and red algae preferred by these damselfishes was largely replaced by brown algae of lower nutritional value during the warm period[108], probably causing a food shortage that curtailed growth rates and left tell-tale check marks in otoliths. The impact of increased ocean temperature on the growth rate of fishes on the GBR is difficult to predict without knowledge of how food availability and feeding behaviour will be affected, and this is likely to be species specific.

Reproduction of fishes on the GBR tends to be highly seasonal, often peaking in spring or early summer, although the precise pattern differs greatly among species[140]. Increasing sea temperature appears to trigger the start of the breeding season in at least some tropical reef fishes[36,40,151,67], including coral trout, *Plectropomus leopardus*, on the GBR[153]. Increased temperatures could cause an earlier start to the breeding season in these species, and possibly a longer breeding season if thermal limits for reproduction are not exceeded. Other species use photoperiod, or a combination of photoperiod and temperature, to cue the start of the breeding season. The timing of reproduction in these species might not be as strongly influenced by elevated temperature, however, their reproductive success could be compromised if higher water temperatures caused a mismatch between the timing of the breeding season and the optimal conditions for survival and dispersal of larvae[49].

Reproduction is only possible within a narrow range of the temperatures that can be tolerated by adults[170]. Consequently, elevated temperatures could depress reproductive success in populations that are already living near their optimal thermal environment for reproduction. Ruttenberg et al.[150] found a bell curve relationship between temperature and mass-specific egg production of southern whitetail major, *Stegastes beebei*, in the Galápagos Islands. Egg production declined from a peak near 25°C to lowest rates at 20°C and 27°C. This suggests that an increase in temperature is not always beneficial to reproductive output. The 1 to 3°C increase of sea temperature predicted for the GBR (Lough chapter 2) could potentially have positive or negative effects on the reproductive output of reef fishes, depending on whether or not they are residing in locations close to their thermal tolerance limits for reproduction. Some species from predominantly temperate water fish families (eg pink snapper, *Pagrus auratus*: Sparidae) already appear to be at their thermal limit for reproduction in tropical water[158] and their populations on the GBR may decline as ocean temperature increases.

Sex determination is temperature sensitive in some marine fishes[44]. For example, individuals in low latitude populations of the Atlantic silverside, Menidia menidia, usually develop into females early in the season when temperatures are low and develop into males late in the season when temperatures are higher[37]. There is currently little evidence for temperature dependent sex determination in GBR fishes.

### 12.2.2 Changes in ocean chemistry

Atmospheric carbon dioxide ($CO_2$) concentrations have increased 30 percent from an estimated 280 parts per million in pre-industrial times to over 370 parts per million today[78]. Depending on emission scenarios, $CO_2$ concentrations are predicted to reach 540 to 979 parts per million by the end of the century[78]. The amount of $CO_2$ dissolved in the ocean increases as atmospheric partial pressure of $CO_2$ increases. Additional $CO_2$ reacts with water to form carbonic acid, which through a series of reactions leads to a decline in pH and a shift in the carbonate-bicarbonate ion balance[50].

Oceanic pH is predicted to drop 0.4 to 0.5 points by 2100[145] (Lough chapter 2). This would make the ocean more acidic than at any time in the past 400,000 years[50]. The sensitivity of tropical marine fishes to changes in pH of this magnitude is largely unknown, although the behaviour of some marine fishes (eg snapper) is sensitive to pH changes only slightly beyond the range predicted[91]. In past decades, the acidification of lakes by atmospheric pollutants has caused significant reductions in the growth rate, reproductive activity and survival of freshwater fishes, which has led to serious declines in populations of some lake species[80]. Although the decrease in ocean pH as a result of climate change is not expected to be as severe as that induced by acid pollution in freshwater lakes, the impact of reducing pH using elevated $CO_2$ levels appears to be more dramatic than an equivalent reduction in pH using acids[79]. Consequently, there is room for concern that elevated levels of dissolved $CO_2$ and decreased pH might have some effect on marine fishes. Fish eggs are much more sensitive to pH changes than are juveniles and adults[24]. Consequently, the largest effects of acidification are likely to be on reproductive performance, which might flow through to population replenishment if the impacts are sufficiently large.

Increased levels of dissolved $CO_2$ not only acidify the ocean, they also act to decrease the pH of animal tissue[131]. In fishes, internal pH level is controlled by the exchange of ions, mostly across the gills, and small changes in internal or external pH can be readily compensated[34]. Although this compensatory

mechanism is not detrimental in the short-term, ultimately it might have some physiological costs, especially for species such as pelagic fishes with high metabolic rates[131].

Reduction in the saturation state of carbonate species (especially aragonite) as a result of elevated levels of dissolved $CO_2$ is expected to have serious consequences for calcification rates of coralline algae, corals, and other calcifying invertebrates[50,88]. This could reduce food supply of some coral, plankton and invertebrate-feeding fishes. A reduced carbonate saturation state could also potentially affect skeletal formation in larval fishes. Skeletal growth in juvenile and adult fishes is not expected to be impacted because these life stages have precise control over their internal ionic environment. Larval fishes, however, are more sensitive to the external environment and changes in the carbonate ion balance of the ocean might be sufficient to retarded skeletal development in early life. Experiments have shown that skeletal calcification of some invertebrates can be retarded at $CO_2$ concentrations well within those predicted to exist by 2100[161]. Whether these levels will have impacts on the skeletal development of larval fish is currently unknown.

### 12.2.3 Changes in ocean circulation

Oceanic, wind-driven and tidal currents contribute to the complex patterns of water flow on the GBR. The south flowing East Australian Current (EAC) and the north flowing Hiri Current are the dominant large-scale oceanographic features of the GBR. These currents form and diverge where the South Equatorial Current meets the Australian continental shelf at about 14°S. The EAC and Hiri currents influence the transportation of heat and nutrients throughout the GBR and the location and intensity of upwelling along the shelf break. Inshore, a northward flowing current runs along the coast, primarily driven by the south-easterly trade winds. In contrast, tides tend to drive water across the shelf. These opposing currents set up complex spatial and temporal patterns of water movement within the GBR lagoon.

Changes to current patterns on the GBR could impact fishes in several ways. First, local- and meso-scale currents appear to play an important role in the retention and dispersal patterns of larval fishes on the GBR[81,26]. Any changes in the strength or direction of these currents could influence larval transport among reefs. Second, circulation patterns influence the production and distribution of plankton[65] (McKinnon et al. chapter 6), which is food for larval and adult fishes. Changes to productivity brought about by the effect of climate change on oceanographic circulation could influence: i) the growth and survival of larval fishes; ii) the growth and distribution of pelagic fishes; and iii) the growth and reproductive success of reef-associated fishes, especially plankton feeders such as caesionids and many pomacentrids, and acanthurids.

The EAC generates areas of upwelling along the GBR shelf break, which results in the injection of nutrient rich water into the GBR lagoon at various locations. Some climate change models predict a general strengthening of the EAC, especially at high latitudes[27]. If these effects extend to lower latitudes we might expect to see impacts on the location, duration or intensity of upwelling along the GBR shelf break. This could periodically increase productivity in some areas and reduce productivity in others (Steinberg chapter 3), with correspondingly positive or negative effects on fishes in these areas. An increase in the strength of the EAC could also influence the migratory patterns of pelagic fishes, especially those that follow the warm summer EAC into southern waters[87].

Planktonic productivity on the GBR is influenced by periodic events that alter nutrient availability, such as freshwater inputs, sediment resuspension from tropical storms, and upwelling of nutrient rich water along the continental slope (McKinnon et al. chapter 6). These events are most pronounced during the summer monsoon, which is also the peak period for fish recruitment on the GBR[47,45,140]. Clearly, any impacts on oceanographic conditions that affect planktonic productivity during this time could have serious ramifications for the growth and survival of larval fishes and their subsequent recruitment to the adult population. Some (but not all) climate models predict a trend towards more El Niño like conditions over the next century[128], which would likely mean a weakened monsoonal influence. This might have a tendency to reduce nutrient enhancing events on the GBR, with potential flow-on effects to productivity. Despite the critical importance of currents and upwelling to the function of the GBR, predictions about the effects of climate change on oceanographic conditions remain highly uncertain and speculative.

Changes to major current patterns elsewhere in the world could also affect the GBR. The global meridional overturning circulation is one of the Earth's major mechanisms of heat transport from the tropics to the poles. It operates through the sinking of cold dense water near the poles and the return of warm surface water from the tropics[73,25]. A reduction in the formation of sea ice at the poles and/or influx of freshwater from the melting of icepacks and glaciers could slow the overturning circulation, with potential impacts at both high and low latitudes. Slowing of the Atlantic meridional overturning circulation has already been reported[25] and this could reduce the rate of warming in the north Atlantic. What impact it might have in the southern hemisphere is unclear, in part because this region is strongly influenced by overturning circulation around Antarctica[128,6]. The likelihood of a complete breakdown of overturning circulation remains highly uncertain[167,94]; however, if it was to occur it could lead to additional warming of tropical ocean water and a more rapid realisation of the issues associated with elevated temperature discussed above.

### 12.2.4 Changes in light and ultraviolet radiation

Eggs and larval stages of marine fishes are highly sensitive to ultraviolet (UV) radiation[188]. These life history stages will almost certainly experience greater mortality if UVB radiation levels increase as a result of climate change. Increased UVB radiation could also have an indirect effect on the growth and mortality of larval fishes due to negative impacts on the planktonic organisms that form the diet of larval fishes. In one of the few studies to have considered the link between solar radiation and the physical condition of larval reef fishes, Bergenius et al.[13] found that the growth rate of larval surgeonfish *Acanthurus chirurgus* was negatively associated with increasing levels of solar radiation. However, the predictions are that climate change will not significantly affect UV radiation levels in the GBR region and exposure to this threat is therefore low.

### 12.2.5 Sea level rise

Nearshore species will be exposed to coastal inundation and associated habitat changes as a result of the predicted 0.1 to 0.9 metre rise in sea level by 2100. Many coastal environments such as mangroves[139] and seagrass beds[119] have important nursery roles, providing juvenile fish with protection[18] or food resources[159]. Consequently, changes in the extent, relative area and proximity of the various habitat types will impact on nursery ground function. The direction of this impact is

likely to vary spatially, determined by the details of specific habitat change, and is likely to be different for particular species, depending on their specific requirements. Juveniles often utilise a mosaic of habitats, particularly in accessing intermittently available intertidal habitats[157], meaning the range of effects of changes in habitat availability will be complex and difficult to predict.

Sea level rise will influence connectivity among meso-scale habitat units such as estuaries, estuarine wetlands and freshwater habitats[160], changing the ability of fish like barramundi, *Lates calcarifer*, to access crucial juvenile habitats[149]. Sea level rise might be expected to enhance connectivity between habitats that are normally isolated at low tide. However, in many cases human responses to mitigate the threat of sea level rise, such as the construction of weirs and other barriers[77], are likely to reduce connectivity. This is a substantial threat to species that require access to wetland habitats since access is already impaired due to past human activities[77,160].

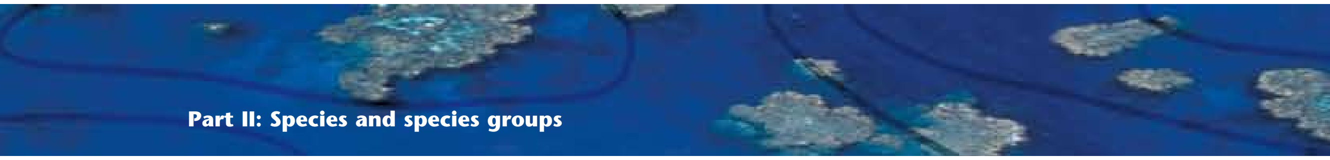
### 12.2.6 Physical disturbance – tropical storms

The frequency of intense cyclones is predicted to increase as a result of climate change[175], although there is still considerable uncertainty about the magnitude of increase that is likely to occur[93]. Tropical cyclones often cause a temporary decline in the abundance of some fishes on impacted reefs[62]. These declines can lag behind the initial impact and are likely due to the loss of critical habitat or food for certain species[184]. Recovery of fish populations occurs as benthic habitat recovers over a period of years to decades[62]. More frequent and larger cyclones will increase the disturbance regime experienced by reef communities, with increased impacts on fish communities at a local scale. A more troubling consequence of increased cyclone activity is the interaction with other disturbances, such as coral bleaching, that also decrease coral cover and degrade habitat structure. The cumulative effect of an increasing number of large-scale disturbances on the physical structure of reefs has the potential to seriously degrade fish communities on the GBR.

### 12.2.7 Rainfall and river flood plumes

Climate change models predict that rainfall patterns will become more extreme by 2100. Consequently, patterns of freshwater input to the GBR lagoon should also become more extreme, although predictions about the magnitude of these changes remain uncertain. Increased peaks in freshwater flow might periodically increase coastal productivity as a result of enhanced nutrient supply in the GBR lagoon. However, any increase will likely be relatively small because the majority of nutrients in the GBR lagoon are made available by resuspension of sediments, not riverine inputs[51]. In addition, increased productivity will be largely confined to coastal waters because flood plumes on the GBR mostly travel alongshore and rarely extend more than 10 to 20 km from the coast[52] (McKinnon et al. chapter 6).

Changes in rainfall and freshwater input are likely to impact species relying on access to wetland habitats. The ability of marine fish to access wetland habitat is influenced by both major flooding and localised flooding from storms[160], as well as by tides. A decrease in the frequency or volume of flooding at either scale will lead to less regular and less extensive connectivity. This could impair the viability of wetland habitats in many areas of the dry tropics, and move some wet tropics wetlands towards the intermittent connectivity currently a feature of the dry tropics.



Beyond direct effects on the ability to access wetlands, any reduction in the amount or regularity of rainfall will impact the viability of wetland pools as fish habitat and nurseries. Estuarine wetland pools range from fully fresh to hypersaline, depending on connectivity patterns[160]. Pools with irregular marine connections undergo a cycle of filling and drying in response to freshwater flows. Extended drought allows freshwater pools to dry or saline pools to develop extremely hypersaline conditions[160]. In either case their function as fish habitats is significantly altered. This is a far-reaching problem because altered rainfall patterns will not only affect the viability of individual pools, it will also reduce the total number of pools available, which have already been reduced by the construction of weirs and pasture ponding[77].

## 12.3 Impacts of climate change on population and communities

Impacts of climate change on fishes will be a combination of direct (eg effect of temperature on physiological processes) and indirect effects (eg impact of coral bleaching on habitat structure). These different effects will interact to influence the life histories, population dynamics, community structure and distributions of fishes on the GBR (Figure 12.1).

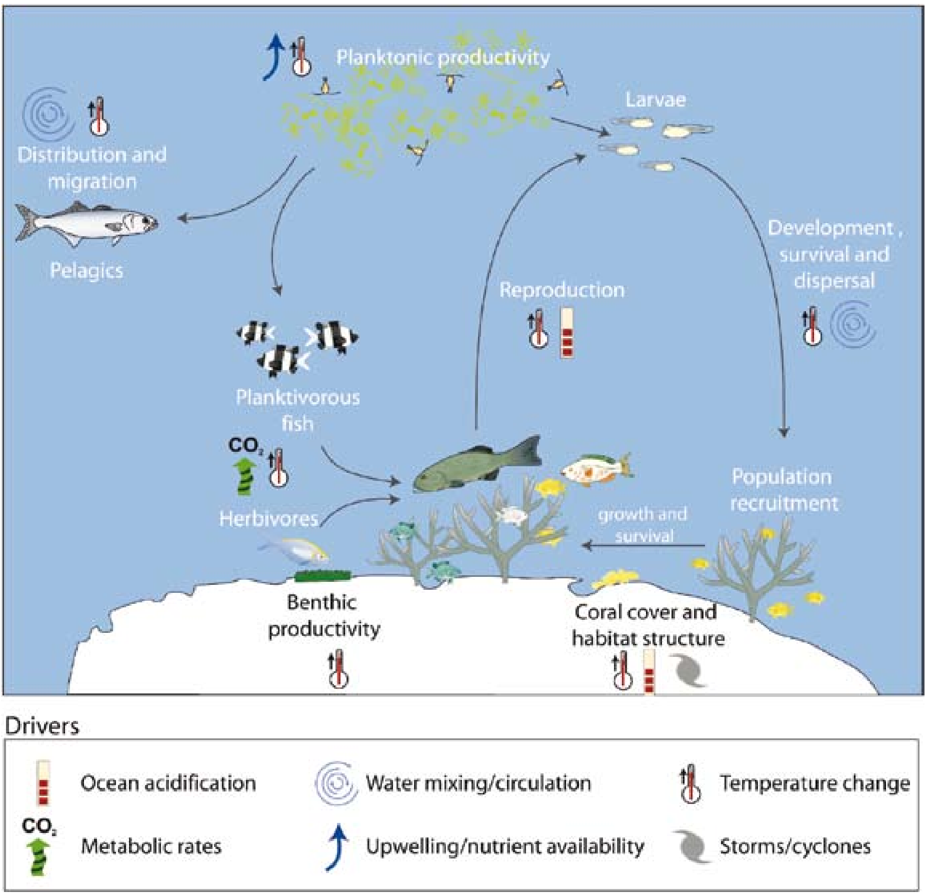
### 12.3.1 Life histories

Changes to the life history patterns of fishes are expected to occur based on permanently elevated sea temperature. Based on variation in life history traits of some tropical reef fishes across temperature gradients we might expect increased sea temperature to generally shift life histories towards: i) smaller maximum size; ii) reduced maximum longevity; iii) earlier maturation; and iv) longer breeding season. These shifts would be observed as long-term trends in mean values for populations at any given location.

Life history traits of reef fishes can differ markedly between populations and much of this variability appears to be influenced by complex interactions between temperature, density, food availability and mortality rates[109,60,33,141,150]. Within-species variations in maximum size and age have been correlated with temperature at geographical[33,141] and local scales[150]. In general, individuals tend to reach smaller maximum sizes and die younger in warmer environments, although there are a number of exceptions to this pattern (eg Kritzer[90], Williams et al.[177]). Age or size at maturation of fishes is often correlated with maximum age or size[17]. Therefore, we expect that the average size or age at maturation will also tend to decrease in populations that experience a shift towards smaller maximum size and younger average age at higher temperatures. Fishes on equatorial coral reefs currently have longer breeding seasons than those on the GBR[164]. Therefore, it is likely that breeding seasons will get longer at higher latitudes, as temperatures gradually increase.

The impact of increased temperature on growth rate is much more difficult to predict because it is highly dependent on food supply. Increased temperature might be expected to increase growth rate within populations (provided they are not already at their thermal optimum), but will only do so if more food can be consumed at higher temperatures. Indeed, some coral reef fishes exhibit an inverse relationship between growth rate and temperature across their geographic ranges[141]. For other species, a smaller size-at-age of individuals at warmer locations is also suggestive of a slower overall growth rate at higher temperatures[33]. At least some of this geographical variation in growth rates

***Figure 12.1*** *Representation of the ways climate change can influence fish populations and communities through a range of direct and indirect effects on different life stages*[a]



is likely caused by differences in food availability, nutritional quality, and population density among locations. The inverse relationship between temperature and growth for some reef-based populations contrasts with the evidence for increased growth rate at higher temperatures for larval fishes[105,183,110]. Consequently, it is possible that higher temperatures will tend to have a positive effect on the growth rate of larvae, but a negative effect on the growth rate of juveniles and adults.

There is already considerable variation in life history and demographic traits of reef fishes across habitat zones on the GBR. For example, parrotfishes on the outer barrier reef grow slower, have higher mortality rates, reach smaller maximum sizes and change sex earlier than individuals of the same species living just 10 to 20 km away on the mid-shelf[61,59]. Fishing pressure also causes variation

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[a] Depends on multiple interactions between the physical environment, metabolic and behavioural responses of larvae and adults, energy transfer between trophic levels, and the effect of habitat structure on ecological interactions.

in the life history traits of exploited species among reefs[2,8]. Consequently, expected changes to life history traits as a result of a 1 to 3°C rise in sea temperature are not expected to be large compared to the natural variation that already exists among populations occupying different parts of the reef, or between fished and unfished populations.

### 12.3.2 Population dynamics

Large-scale population dynamics of many pelagic and non-reef marine fishes appear to be driven by fluctuations in the physical environment. Year class strength of several important fisheries species in the northeast Pacific have been linked to variation in temperature and oceanographic conditions over years to decades[72]. Multi-decadal cycles of sardine and anchovy abundances are correlated with fluctuation in temperature and productivity[30] and increases in horse mackerel abundance in the North Sea are correlated with increased temperature and higher plankton abundance, possibly driven by changes in currents[138]. These examples demonstrate that complex interactions between atmospheric forcing, hydrographic fluxes and productivity can affect the population dynamics of marine fishes.

In the tropical Pacific Ocean, population dynamics of tuna species (eg skipjack, *Katsuwonus pelamis*; yellowfin *Thunnus albacares* and bigeye, *Thunnus obesus*) fluctuate on multi-year cycles associated with the presence or absence of warm El Niño conditions[95,102,130]. Where the underlying causes of these fluctuations have been determined, it seems that changes in the distribution and abundance of smaller prey fish are largely responsible[129]. Small planktivorous fishes, which are the prey of tunas, shift their distributions in accordance with changes in the location of highly productive upwelling and convergence zones during El Niño events[95,30,130]. The tight coupling between temperature, hydrology and productivity indicates that any changes to oceanographic conditions in the tropical western Pacific as a result of climate change could influence the abundance of pelagic fishes in the GBR region. This notion is supported by the observation that black marlin, *Makaira indica*, seem to be more abundant off the Queensland coast during warm El Niño years and blue marlin, *Makaira mazara*, more abundant during cooler years[180]. In general, however, predictions about how climate change will affect oceanographic conditions currently lack sufficient certainty to assess the consequences for pelagic fishes on the GBR.

Reef fish abundances fluctuate based on variation in the supply of new recruits to the population and the effects that predation, competition and disturbance have on the survival of recruits after they join the reef-based population[83,28,46]. The most significant impacts of any changes to oceanographic conditions on the abundance of reef-associated fishes will likely come through effects on the growth, survival and dispersal of larvae. Wilson and Meekan[183] found that the magnitude of recruitment to bicolor damselfish, *Stegastes partitus*, populations in San Blas was positively correlated with larval growth, with large recruitment pulses containing the fastest growing larvae. Growth rate of larvae was positively correlated with water temperature and wind speed, both of which are likely to affect food availability or feeding efficiency of larval fishes[38]. Larger and better conditioned larvae are also more likely to survive after they settle to the reef[84]. Consequently, it seems that changes to pelagic productivity within the GBR lagoon, or feeding efficiency of reef fish larvae, could influence the replenishment of reef fish populations. Indeed, one recent study[31] found synchronised increases in the population size of damselfish species on the GBR following warm El Niño conditions, which suggests that altered conditions improved the survival of larval and juvenile fishes during the warmer period.

Currents and tides potentially play an important role in the retention and dispersal of larval fishes on the GBR[81,26]. Clearly, any changes to circulation patterns as a result of climate change could have fundamental effects on the spatial and temporal patterns of larval supply to individual reefs and the degree of connectivity among reefs. Changes to circulation patterns could also interact with changes to productivity to affect how many larvae survive the pelagic stage and their condition at settlement (Figure 12.1). For example, strong year classes of several damselfishes in the Galápagos Islands are correlated with warm El Niño events[109], suggesting that changed oceanographic conditions in these years improved their pre- and post-settlement survival. Increased sea temperature could also modify connectivity between reefs through affects on larval development and behaviour. Theoretical models predict that the spatial scale of larval dispersal is highly sensitive to the ontogenetic timing of reef-seeking behaviour and active swimming ability[4,39]. Therefore, the scale of dispersal between reefs might be reduced if larval development and swimming ability is accelerated in warmer conditions.

Overall, the uncertainty of how climate change will affect oceanographic conditions on the GBR, and our lack of understanding of how larvae will respond to changes in the physical environment, prevent us from making robust predictions about the consequences of climate change to the dynamics of reef fish populations. All we can say is that there is the potential for significant and widespread impacts.

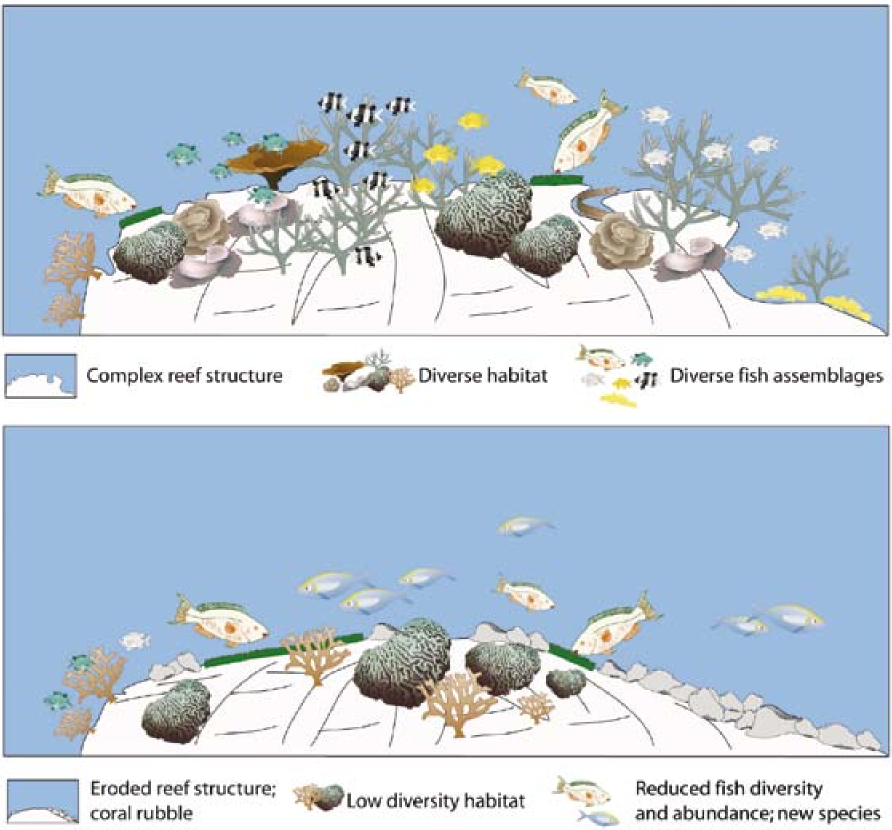
### 12.3.3 Community structure

The frequency of coral bleaching on the GBR is predicted to increase as sea temperature rises[68,75]. Regular bleaching of large areas of the GBR will change the composition of benthic reef communities and lead to fundamental shifts in the composition of the associated fish communities. Declines in live coral cover, changes in the species composition of remaining corals, and a loss of habitat complexity will all combine to decrease the diversity and abundance of reef fish assemblages and alter their species composition[114] (Figure 12.2).

Some reef fishes are obligate coral dwellers[116,53], some feed on live coral tissue[132] and many others preferentially settle into live coral[21,122,71]. These species are the ones most immediately affected by declining coral cover[89,163,113,184]. However, the majority of fishes associated with coral reefs are not directly dependent upon living corals. Based on current knowledge, we estimate the proportion of species that are coral dependent in reef fish communities on the GBR to be slightly less than 10 percent (or 107 of 1220 species listed in Randall et al.[137], a figure similar to elsewhere in the Indo-Pacific[85]. Some reef fish families are more reliant on corals than others, with a higher proportion of species in diverse reef fish families such as butterflyfish (Chaetodontidae), cardinalfish (Apogonidae) and gobies (Gobiidae) directly at risk from loss of corals (Figure 12.3). There is also a potential threat to higher taxonomic levels of reef fish biodiversity, with all species of some specialised genera (eg *Gobiodon, Paragobiodon*) and an entire family of reef fishes, the crouchers (Caracanthidae – represented by only two species) highly dependent upon corals. Many of these fish-coral relationships are species-specific and so the magnitude of the threat depends on the susceptibility of particular coral species to bleaching, combined with the degree of coral-specialisation of the fish species[113].

Although only one in ten coral reef fishes are directly coral-dependant, community responses to loss of coral cover extend to a greater range of species. Jones et al.[85] documented a dramatic decline in diversity of reef fish species on coastal reefs in Papua New Guinea following a severe loss of live coral

***Figure 12.2*** *Continued degradation of reef habitats has implications for diversity, abundance and community structure of reef fish assemblages*[b]



(coral cover declined from approximately 66 to 7%). Seventy five percent of fish species declined in abundance, with 50 percent of species declining by more than 50 percent, and only a relatively small number of species increased in abundance. This response to declining coral cover does not appear to be particularly unusual. In a recent meta-analysis, Wilson et al.[184] found that an average of 62 percent of reef fish species declined in abundance following a loss of at least 10 percent coral cover, and 29 percent of these species exhibited a decline in all the studies included. Declines in abundance were greatest among coral-dwellers and coral feeders, however, some invertebrate feeders and planktivores also declined in abundance.

Many reef fishes preferentially settle near live coral[85], even if adults are not coral dependent. This might be one of the reasons why a broad range of species exhibit a response to large-scale coral loss. A general degradation of habitat, and perhaps a suppression of settlement cues, could also contribute

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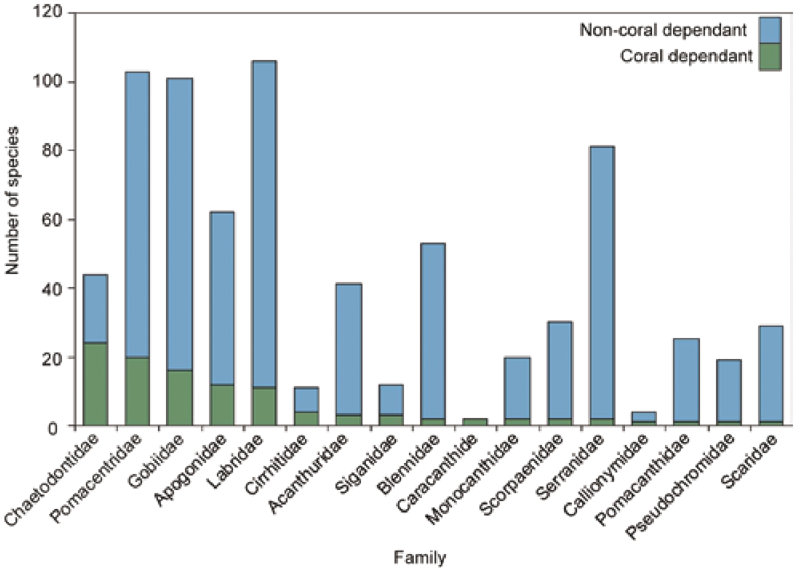
[b] Loss of coral cover and structural complexity causes a gradual loss of species richness, reduced abundances, and a shift towards communities containing more generalist and fewer specialist species.

**Figure 12.3** Families of fishes on the GBR with one or more coral-dependent species[c]



to a decline in settlement following bleaching. For example, recruitment of three species of common damselfish at One Tree Island declined following the 1998 bleaching event, even though only one of these species recruits to live coral[20]. This indicates that negative impacts of habitat degradation on coral reefs are not necessarily restricted to species that have an intimate association with living coral and that the permanent loss of coral cover can have far-reaching effects on the composition of reef fish communities. The species most likely to benefit from coral loss and reef degradation are some of the small generalist species and herbivores that live in areas of low relief and rubble, such as various gobies, blennies and damselfishes[168,10].

The changes so far detected within fish assemblages in response to declining coral cover might not give a complete picture of the long term impacts of coral loss because population declines may take years to emerge, especially for long lived species. Declines in the abundance of obligate coral feeding butterflyfish at Trunk Reef, GBR, following a catastrophic loss of live coral (greater than 90% decline) took over two years to become apparent[134]. This indicates that adults of some coral dependent species are able to persist for a considerable time following a loss of coral habitat or food. Rather than immediate responses to coral loss, we might often see slow population declines due to increased attrition of adults and reduced replenishment by recruits. Loss of coral can have serious effects on the growth[89] and body condition[133] of corallivorous species, which will likely flow on to the reproductive success of the population. Therefore, the negative effects of habitat loss on the survival of adults and the availability of substratum for the settlement of new recruits might also be reinforced by a general decline in the abundance of larvae to replenish local populations.

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[c] The number of species estimated to be coral dependent (green) is shown as a component of the total number of species listed for each family in Randall et al.[137] (blue).

The diversity of reef fish communities is often correlated with habitat structure[83,168]. Reefs with high structural complexity support more individuals and more species than reefs with low structural complexity. Many of the corals most susceptible to coral bleaching are also the ones with the highest structural complexity[107]. Loss of these coral species will reduce habitat complexity on reefs. Continued bleaching will cause further loss of structural complexity through erosion of the reef matrix as coral recruitment and growth struggles to keep pace with coral mortality. If the frequency of bleaching increases as predicted, we can expect an overall decline in the structural complexity of coral reefs on the GBR, with a corresponding decline in the diversity and abundance of the associated fish communities[100,56] (Figure 12.2). Herbivores often increase in abundance following a loss of coral cover[184], presumably because more area becomes available for algal growth following coral bleaching, however, even these species ultimately decline as habitat structure is lost[154,54].

Recent studies indicate that fish communities on the GBR have considerable resilience to disturbance and can recover from cyclones and bleaching events over years to decades, provided that benthic habitat recovers[62]. Elsewhere, where not all coral species have recovered, the recovery of fish communities has also been incomplete[15] or there have been phase shifts to communities with fewer coral specialists and more habitat generalists[10]. The consequences of habitat loss on GBR fish communities will depend on the frequency and intensity of bleaching events, combined with the impacts of other disturbances, relative to the potential for the reefs and their associated fish communities to rebound. Fish communities on inshore reefs are at greatest risk because these reefs are often the ones most impacted by coral bleaching[14] and have greater exposure to the effects of sedimentation and pollution from terrestrial sources. Fish species that are not directly associated with coral reefs, such as many coastal, inter-reef and pelagic species are less likely to be impacted by the loss of reef habitat.

### 12.3.3 Distributions and range shifts

Biogeographic range shifts are one of the clearest signatures of climate change impacts in animal communities[125]. Range shifts towards higher latitudes, correlated with higher than average ocean temperature, have been observed in a substantial number of temperate marine fishes. For example, a change in the structure of the nearshore fish community in the Southern California Bight from one dominated by northern (cold affinity) species to one dominated by southern (warm affinity) species corresponded with a rapid increase in mean sea surface temperature of approximately 1°C in 1996 to 1997[70]. A similar increase in mean sea surface temperature appears to explain the northward shift in the range of 13 species of marine fishes in the North Sea between 1977 and 2001[127] and a 1 to 6°C elevation in sea temperature was associated with the appearance of 29 new species of tropical fishes off the coast of North Carolina[124].

Most species of fish on the GBR are cosmopolitan in distribution. However, a considerable number of species appear to have distributions concentrated in the northern half of the GBR (see Table 12.1 for examples). A smaller number of species have distributions limited to the southern half of the GBR (see Table 12.2 for examples). Changes in the distributional extent or relative abundance of fishes on the GBR will almost certainly occur as a result of the predicted 1 to 3°C increase in mean sea temperature by 2100. Warming is predicted to be greater in the southern half of the GBR compared to the northern half (Lough chapter 2). Over 90 species of fishes from the northern half of the GBR do

not currently occur, or are relatively uncommon, in the southern or far-southern regions of the GBR (Table 12.1). Some of these species will expand their southern limits as temperature increases. Few changes are likely to the northern range limits of fishes already resident on the northern half of the GBR because the magnitude of temperature changes will be smaller and many of these species have ranges that extend into equatorial regions, where the mean ocean temperature is already warmer than that currently experienced on the GBR. The Whitsunday region appears to be an important biogeographic boundary for many northern range GBR fishes (M Emslie pers comm) and we expect that range extension will mostly be south of this region.

***Table 12.1*** *Some GBR fish species restricted to, or most abundant on, the northern half of the Great Barrier Reef (Derived from Russell[148], Kuiter[92], Randall et al.[137] and Randall[136])*

| Family | Species | Common Name | Distribution |
|---|---|---|---|
| Pomacanthidae | *Centropyge aurantia* | Golden Angelfish | Northern GBR |
| | *Centropyge loriculus* | Flame Angelfish | Northern GBR |
| | *Centropyge multifasciata* | Multi-barred Angelfish | Northern GBR |
| | *Geniacanthus lamarck* | Lamarck's Angelfish | Northern GBR |
| | *Pomacanthus navarchus* | Blue-girdled Angelfish | Northern GBR* |
| | *Pomacanthus xanthometopon* | Blueface Angelfish | Northern GBR |
| Chaetodontidae | *Chaetodon rafflesi* | Latticed Butterflyfish | Northern GBR* |
| | *Chaetodon ocellicaudus* | Spot-tail Butterflyfish | Northern GBR |
| | *Chaetodon reticulatus* | Reticulate Butterflyfish | Northern GBR* |
| | *Chaetodon semeion* | Dotted Butterflyfish | Northern GBR |
| Pomacentridae | *Amblypomacentrus breviceps* | Black-banded Damsel | Northern GBR* |
| | *Cheiloprion labiatus* | Big-lip Damsel | Northern GBR |
| | *Chromis delta* | Deep-reef Puller | Northern GBR |
| | *Chromis xanthochira* | Yellow-axil Puller | Northeastern Australia |
| | *Dascyllus melanurus* | Black-tailed Humbug | Northeastern Australia |
| | *Lepidozygus tapeinosoma* | Fusilier Damsel | Northern Australia* |
| | *Neopomacentrus cyanomos* | Regal Demoiselle | Northern Australia* |
| | *Pomacentrus adelus* | Obscure Damsel | Northern Australia |
| | *Pomacentrus nigromarginatus* | Blackmargin Damselfish | Northern GBR |
| | *Pomacentrus reidi* | Grey Damsel | Northeastern Australia* |
| | *Amphiprion chrysopterus* | Orangefin Anenomefish | North Queensland* |
| | *Amphiprion percula* | Eastern Clown Anenomefish | North Queensland* |
| | *Premnas biaculeatus* | Spine-cheek Clownfish | North Queensland* |
| Holocentridae | *Myripristis adusta* | Shadowfin Soldierfish | Northern Australia |
| | *Myripristis vittata* | Whitetip Soldierfish | Northern Australia |
| | *Neoniphon opercularis* | Blackfin Squirrelfish | Northern Australia |

| Family | Species | Common Name | Distribution |
|---|---|---|---|
| | *Sargocentron punctatissimum* | Speckled Squirrelfish | Northern Australia |
| | *Sargocentron spiniferum* | Sabre Squirrelfish | Northern Australia* |
| | *Sargocentron violaceum* | Redface Squirrelfish | Northern Australia |
| Solenostomidae | *Doryrhamphus janssi* | Cleaner Pipefish | Northern Australia |
| | *Doryrhamphus dactyliophorus* | Banded Pipefish | Northern Australia |
| | *Corythoichthys ocellatus* | Ocellated Pipefish | Northern GBR |
| | *Halicampus mataafe* | Samoan Pipefish | Northern GBR |
| | *Hippocampus bargibanti* | Pygmy Seahorse | Northern GBR |
| Serranidae | *Pseudanthias dispar* | Fairy Basslet | Northern GBR |
| | *Pseudanthias huchtii* | Pacific Basslet | Northern GBR |
| | *Pseudanthias lori* | Lori's Basslet | Northern GBR |
| | *Pseudanthias luzonensis* | Luzon Basslet | Northern GBR |
| | *Pseudanthias smithvanizi* | Princess Basslet | Northern GBR |
| | *Serranocirrhitus latus* | Swallowtail Basslet | Northern GBR |
| | *Luzonichthys waitei* | Pygmy Basslet | Northern GBR |
| | *Cephalopholis leopardus* | Leopard Rockcod | Northern Australia* |
| | *Gracilia albomarginata* | White-square Cod | Northern GBR* |
| | *Plectropomus laevis* | Bluespotted Coral Trout | Northern GBR* |
| | *Plectropomus oligocanthus* | Vermicular Cod | Northern GBR |
| | *Belonoperca chabanaudi* | Arrowhead Soapfish | Northern GBR |
| | *Liopropoma multilineatum* | Yellow Reef Basslet | Northern Australia |
| Pseudochromidae | *Pseudochromis bitaeniatus* | Slender Dottyback | Northern GBR |
| | *Pseudochromis flammicauda* | Orangetail Dottyback | Northern GBR |
| Plesiopidae | *Assessor flavissimus* | Yellow Scissortail | Northern GBR |
| Apogonidae | *Ostorhinchus compressus* | Blue-eyed Cardinalfish | Northern Australia |
| | *Ostorhinchus fragilis* | Fragile Cardinalfish | Northern Australia |
| | *Ostorhinchus hoeveni* | Frostfin Cardinalfish | Northern Australia |
| | *Ostorhinchus lateralis* | Pinstripe Cardinalfish | Northern GBR |
| | *Ostorhinchus sangiensis* | Sangi Cardinalfish | Northern GBR |
| | *Archamia zosterophora* | Girdled Cardinalfish | Northern GBR |
| | *Sphaeramia nematoptera* | Pajama Cardinalfish | Northern Australia |
| Carangidae | *Alepes vari* | Herring Scad | Northern Australia |
| | *Carangoides humerosus* | Epaulette Trevally | Northern Australia* |
| | *Carangoides plagiotaenia* | Barcheck Trevally | Northern Australia |
| Lutjanidae | *Lutjanus bohar* | Red Bass | Northern Australia* |
| | *Lutjanus decussatus* | Checkered Snapper | Northern Australia |
| | *Lutjanus ehrenbergii* | Ehrenberg's Snapper | Northern Australia |
| | *Lutjanus johnii* | Golden Snapper | Northern Australia |

| Family | Species | Common Name | Distribution |
|---|---|---|---|
| | *Lutjanus semicinctus* | Blackbanned Snapper | Northern GBR |
| | *Macolor macularis* | Midnight Snapper | Northern Australia* |
| Lethrinidae | *Lethrinus harak* | Thumbprint Emperor | Northern Australia |
| | *Lethrinus erythracanthus* | Orangespotted Emperor | Northern Australia |
| Nemipteridae | *Scolopsis affinis* | Bridled Monocle Bream | Northern Australia* |
| | *Scolopsis margaritifer* | Pearly Monocle Bream | Northern Australia |
| Caesionidae | *Pterocaesio tile* | Neon Fusilier | Northern GBR |
| Scaridae | *Scarus japanensis* | Redtail Parrotfish | Northern GBR |
| | *Scarus quoyi* | Greenblotch Parrotfish | Northern GBR |
| Blenniidae | *Ecsenius australianus* | Australian Combtooth Blenny | Northern GBR |
| | *Ecsenius midas* | Midas Combtooth Blenny | Northern GBR |
| | *Meiacanthus luteus* | Yellow Fangblenny | Northern Australia |
| Gobiidae | *Amblyeleotris fontanesii* | Giant Shrimp Goby | Northern Australia |
| | *Amblygobius bynoensis* | Bynoe Goby | Northern Australia* |
| | *Bryaninops natans* | Purple-eyed Goby | Northern GBR |
| | *Exyrias bellissimus* | Mud-Reef Goby | Northern GBR |
| | *Exyrias puntang* | Puntang Goby | Northern GBR |
| | *Eviota bifasciata* | Twostripe Eviota | Northern GBR |
| | *Eviota nigriventris* | Red-and-black Eviota | Northern GBR |
| | *Eviota pellucida* | Neon Eviota | Northern GBR |
| | *Nemateleotris decora* | Purple Firegoby | Northern GBR |
| | *Phyllogobius platycephalops* | Flathead Sponge Goby | Northern GBR |
| | *Trimma tevegae* | Bluestripe Pygmygoby | Northern GBR |
| | *Valenciennea randalli* | Greenband Glider Goby | Northern GBR |
| Acanthuridae | *Ctenochaetus tominiensis* | Orange-tip Bristletooth | Northern GBR |
| | *Naso thynnoides* | OnespineUnicornfish | Northern GBR |
| | *Naso caeruleacauda* | Blue Unicornfish | Northern GBR |
| | *Naso minor* | Blackspine Unicornfish | Northern GBR |
| Siganidae | *Siganus javus* | Java Rabbitfish | Northern Australia |
| | *Siganus punctatissimus* | Spotted Rabbitfish | Northern GBR |
| Tetraodontidae | *Canthigaster papua* | Netted Toby | Northern GBR |
| Ostraciidae | *Ostracion solorensis* | Striped Boxfish | Northern GBR |

* Less abundant, uncommon or rare on the southern GBR

***Table 12.2*** *Some GBR fish species restricted to, or more abundant on, the southern half of the Great Barrier Reef (Derived from Russell[148], Kuiter[92], Randall et al.[137] and Randall[136])*

| **Family** | **Species** | **Common Name** | **Distribution** |
|---|---|---|---|
| Pomacanthidae | *Chaetodontoplus conspicillatus* | Conspicious Angelfish | Southern GBR and Coral Sea |
| | *Chaetodontoplus meridithi* | Yellowtail Angelfish | Southern GBR and NSW |
| Chaetodontidae | *Chaetodon geuntheri* | Gunther's Butterflyfish | Southern GRB and NSW |
| Pomacentridae | *Chromis nitida* | Yellowback Puller | Central and southern GBR |
| | *Neoglyphidion polyacanthus* | Multispine Damselfish | Southern GBR |
| | *Parma polylepis* | Banded Scalyfin | Southern GBR and NSW |
| | *Pomacentrus australis* | Australian Damsel | Southern GBR and NSW |
| Serranidae | *Epinephelus undulatostriatus* | Maori Rockcod | Southern GBR and NSW |
| | *Pseudanthias pictilis* | Painted Basslet | Southern GBR* |
| Aploactinidae | *Neoaploactis tridorsalis* | Threefin Velvetfish | Southern GBR |
| Pseudochromidae | *Ogilbyina novaehollindae* | Multicoloured Dottyback | Southern GBR |
| Plesiopidae | *Paraplesiops poweri* | Northern Blue Devil | Central and southern GBR |
| Apogonidae | *Archamia leai* | Lea's Cardinalfish | Southern GBR and Coral Sea |
| | *Ostorhinchus flavus* | Brassy Cardinalfish | Southern GBR |
| | *Ostorhinchus capricornis* | Capricorn Cardinalfish | Capricorn Group and south |
| Carangidae | *Seriola lalandi* | Yellowtail Kingfish | Southern Australia |
| Sparidae | *Pagrus auratus* | Snapper | Southern Australia |
| Lethrinidae | *Gymnocranius audleyi* | Collar Sea Bream | Southern GBR |
| | *Lethrinus miniatus* | Redthroat Emperor | South of 18 degrees |
| Pempheridae | *Pempheris analis* | Bronze Bullseye | Southern GBR |
| Cheilodactylidae | *Cheilodactylus vestitus* | Crested Morwong | Southern GBR and NSW |
| Labridae | *Anampses femininus* | Bluetail Wrasse | Southern GBR |
| | *Choerodon venustus* | Venus Tuskfish | Southern Queensland |
| | *Coris aurilineata* | Goldlined Wrasse | Southern GBR |
| | *Cirrhilabris laboutei* | Laboute's Wrasse | Southern GBR and Coral Sea* |
| | *Macropharyngodon choati* | Choat's Wrasse | Southern GBR* |
| | *Pseudolabrus guentheri* | Gunther's Wrasse | Southern GBR |
| | *Suezichthys devisi* | Australian Rainbow Wrasse | Southern GBR and NSW |

| Family | Species | Common Name | Distribution |
|---|---|---|---|
| Blenniidae | *Petroscirtes fallax* | Yellow Sabretooth Blenny | South of 17 degrees |
| | *Cirripectes alboapicalis* | Whitedotted Blenny | Southern GBR |
| | *Stanulus talboti* | Talbot's Blenny | Southern GBR |
| Gobiidae | *Istigobius hoesei* | Hoese's Sandgoby | Southern GBR and NSW |
| Acanthuridae | *Prionurus maculatus*<br>*Prionurus microlepidota* | Spotted Sawtail<br>Australian Sawtail | Southern GBR<br>Southern GBR |

* Less abundant on northern GBR

In contrast to range expansions by northern species, some species that are currently confined to the southern half of the GBR (Table 12.2) may become more geographically restricted as sea temperature increases. The latitudinal range of coral reefs is not expected to expand significantly in response to increasing sea temperature because coral growth is limited by light and carbonate alkalinity in addition to temperature[69]. Some southern GBR species are confined to coral reefs and are unlikely to persist in non-reef areas, even if temperatures become more favourable at higher latitudes. Consequently, contracting northern range limits of these species would not be matched by expanding habitat at the southern end of their ranges. The smaller ranges of fishes restricted to the southern and far southern GBR would ultimately increase their risk of extinction from other impacts.

Seasonal transport of coral reef fish larvae into temperate regions by the EAC is a regular occurrence[22]. The frequency of these incursions, and the number of species arriving in southern locations, could increase with increasing sea temperature and potential increases in the strength of the EAC at higher latitudes[27]. The ability of tropical species to establish permanent populations at higher latitudes will depend on their degree of dependence on coral reefs for food, shelter, and reproduction, their tolerance to lower minimum temperatures in winter, and competition from established sub-tropical and temperate water species. Some species of fishes common on coral reefs already have populations beyond the latitudinal extent of coral reef (eg neon damselfish, *Pomacentrus coelestris*; banded goby, *Amblygobius phalaena*; yellowtail fang blenny, *Meiacanthus atrodorsalis*; yellowbar sandperch, *Parapercis xanthozona*; yellow-brown wrasse, *Thalassoma lutescens*; surge wrasse, *T. purpureum*; pennant coralfish, *Heniochus acuminatus*)[35,137] and these species will probably expand their southern range limits as sea temperature increases. However, the appearance of entire communities of coral reef fishes in locations much further south than their current distributions is unlikely within the next 50 to 100 years.

Interannual range limits of pelagic species frequently track ocean temperature[117,130]. Many of the larger pelagic species found in GBR waters, such as mackerel, tuna and marlin have components of their populations that migrate to higher latitudes in summer[87]. For these species, increased sea temperature is likely to result in an earlier timing of seasonal migrations and perhaps an extension of the southern limit of the migration.

## 12.4 Adaptive capacity

Heritable changes in seasonal life history events that correspond with climate change have already been detected in a number of terrestrial animals[23]. Changes in the timing of reproduction, length of the growing season, and the location of over wintering sites have all been found to involve genetic change. In each case, the phenotypic change corresponds to an increase in fitness under the new climate regime. This indicates that genetic adaptation to climate change is already underway in some animal populations.

Populations of fishes on the GBR experience seasonal variations in temperature greater than the 1 to 3°C increases predicted for the GBR. Many reef fishes also have very large geographic ranges, covering a temperature gradient larger than the predicted change. Importantly, some species also have populations extending into equatorial regions where the maximum temperature is already similar to that predicted to occur on the southern half of the GBR by the end of the century. These observations indicate that most GBR fishes could accommodate relatively small increases in sea temperature, either as a result of phenotypic plasticity (acclimation) of resident populations, or gene flow from more northern populations.

There is evidence for strong genetic connectivity among populations of fishes on the GBR[48,111,7]. This has two consequences. First, southern populations might already contain considerable tolerance to higher temperatures due to regular genetic input from northern populations. Second, gene flow from northern populations might assist southern populations to adapt to increasing temperatures in the future. The potential for genetic adaptation will also depend on generation time. Many coral reef fishes are long lived (eg 40 plus years for some acanthurids, serranids and lutjanids[33,126]) and there is little hope of genetic adaptation in local populations of these species within the next 50 to 100 years unless there is substantial genetic input from populations that already inhabit warmer waters. The short generation times of some smaller species, however, might enable local genetic adaptation to occur. For example, many goby species are annuals[66,43], which means there is an opportunity for selection to occur over 50 to 100 generations before the end of the century.

Although acclimation or adaptation to increased temperature seems possible, especially for short-lived species, there is little prospect of adaptation to habitat degradation. Some reef fishes depend on live coral at one or more critical life stages[85]. Many more require complex habitat structure to escape predators[16,168,3]. Significant declines in fish diversity following large-scale loss of live coral[184] and further declines following loss of habitat structure[54,56] indicate that many species are unable to persist once their habitat has seriously degraded. There is little prospect of genetic adaptation under these circumstances. Habitat degradation will also retard genetic adaptation to other climate change impacts (eg increased temperature) by reducing genetic variability within populations (decreased population size) and by reducing genetic connectivity between populations (smaller and more patchily distributed populations).

The consequences of strong genetic selection to climate change impacts are largely unknown. One potential problem is that intense selection to one environmental factor (eg temperature) could reduce the genetic capacity to adapt to other environmental changes[86]. Unfortunately, our understanding of genetic adaptation in tropical marine fishes is at such a rudimentary stage that it is difficult to predict the long-term genetic consequences of climate change on GBR fish populations.

## 12.5 Linkages and fisheries implications

The different impacts of climate change will interact with each other and with other threats and stressors to coral reefs, potentially leading to synergistic or cumulative effects that exacerbate the problem. For example, increased bleaching and increased cyclone disturbance will have cumulative effects on the degradation of coral reef habitat. These impacts could interact with terrestrial pollution to further degrade benthic communities, or even cause a regime shift from coral to algal dominated reefs. Although certain reef fish may play a key role in maintaining coral reef functions[9], the majority of fish species are likely to respond to coral reef regime shifts rather than being the cause of them. A regime shift on GBR coral reefs will almost certainly cause a loss of diversity, especially among coral dependent species, and a shift towards communities containing fewer specialist and more generalist species[113,10]. While the loss of species in high diversity communities may have little impact on the ecosystem as a whole, the shear number of species that are potentially threatened is cause for concern.

The long-term implications of predicted changes to fish populations and communities for ecosystem processes are a matter for speculation only. Given the likely links between biodiversity and ecosystem processes such as productivity (eg Tilman[169], Loreau[101]), it is possible that a decline in reef fish biodiversity will lead to a reduction in energy transfer to higher trophic levels, which may mean that with climate change, reefs will support a reduced biomass of higher order predators. However, changes to primary productivity in plankton and on the reef are likely to be of greater significance. Changes to primary and secondary productivity brought about by climate change could flow on to species at high trophic levels (Figure 12.1), some of which are important fisheries species (eg coral trout). However, no clear predictions can be made about how trophic structure and biomass might be affected, because the net impact of climate change on productivity is highly uncertain and is likely to vary from place to place – there might be positive effects on biomass in some locations and negative effects in others.

It is generally accepted that climate change has had, and will continue to have, profound impacts on the distribution and productivity of the worlds' fisheries[106]. Numerous studies have demonstrated a strong link between climatic changes, such as El Niño and La Niña events, and the distribution or productivity of exploited fish populations[95,121,187,123]. However, these impacts tend to be species or fisheries-specific[96], making it difficult to predict the magnitude and direction of changes in fisheries productivity arising from environmental change. The consensus is that while some fisheries will be negatively impacted by climate change, others may benefit[106].

Compared with many other fisheries around the world, fisheries in the GBR region are generally well managed and are not considered overexploited[182,41,42]. Climate change will almost certainly have some impact on the productivity of GBR fisheries, with implications for sustainable harvest levels. However, predicting the relative importance of these impacts is extremely difficult, because of uncertainty in climate change predictions for the region, the wide range of possible effects of climate change on fish population dynamics, life histories and distribution, and the confounding effects of fishing. Nevertheless, it is clear that climate change can exacerbate population declines or hinder recovery of stocks that are already overfished[186]. This increases the importance of ensuring that fish stocks in the GBR are not over exploited as they are forced to deal with climate change over the next 50 to 100 years.

One area of concern for fisheries productivity is the potential for climate change to affect the relationship between stock size and recruitment. Changes to ocean circulation, temperature, and productivity could potentially interact to change the survival and dispersal patterns of fish larvae. Fisheries productivity could decline if environmental changes result in fewer recruits reaching adult populations. A change in larval dispersal and survival may also result in reduced gene flow and a more fragmented stock structure, which could further reduce the sustainability of fish stocks. Unfortunately, we do not know enough about how climate change will affect larval survival and dispersal to predict if stock-recruitment relationships will be disrupted to the extent where fisheries productivity will be significantly impacted.

Variation in life history traits of exploited species has important implications for sustainability of fisheries[8,178]. Populations with different life histories may respond differently to similar levels of fishing pressure and, therefore, may require different management strategies. Given the prediction that increased temperature will result in a shift in life histories of some species towards smaller size, earlier maturation and reduced longevity, populations of exploited species might be expected to become less vulnerable to fishing pressure. However, the total population biomass may decline if food resources do not increase as temperature increases. Ultimately, local populations may tend towards faster population turnover, but with lower exploitable biomass.

Most species of commercial importance on the GBR are broadly distributed, and their distributions are not likely to be significantly affected by climate change in the short to medium term. However, one important commercial and recreational species, *Lethrinus miniatus* (sweetlip or redthroat emperor), has a restricted anti-equatorial distribution with an apparent upper thermal limit of about 28°C. On the GBR, *L. miniatus* is restricted to south of 18°S where the impact of climate change on water temperature is predicted to be greatest (Lough chapter 2). With a potential longevity of at least 20 years *L. miniatus* is unlikely to adapt quickly to environmental change[177]. Therefore, its distribution on the GBR will likely be reduced as water temperature increases. This will affect the distribution of fishing effort and potentially reduce fisheries productivity. A number of other exploited species in the GBR region exhibit seasonal (scombrids) or ontogenetic (lutjanids) movement patterns. These movement patterns may be affected by climate change through shifts in ocean currents, changes in prey availability, or behavioural responses to increased water temperature. Changes in movement patterns are likely to alter the distribution and timing of fishing effort, but alone are unlikely to significantly impact on fisheries productivity.

## 12.6 Summary and recommendations

### 12.6.1 Major vulnerabilities to climate change

Climate change will have significant impacts on fishes of the GBR. The most immediate and identifiable effects will be changes in the community composition of reef-associated species due to habitat degradation. Reef habitat will continue to degrade if the intensity and/or frequency of coral bleaching increases as predicted. Loss of coral cover will be exacerbated by increased physical disturbance from tropical storms and other stressors. There is now ample evidence that large-scale declines in coral cover can have serious consequences for the structure of reef fish assemblages. Coral-dependant fishes suffer the greatest declines in abundance as a result of coral loss. However,

some species that do not appear to have strong affiliations with live coral also decline in abundance following persistent loss of coral cover.

Population declines may take several years to become apparent because adults of many species can persist for a relatively long time in the absence of live coral. Reef fish diversity and abundance will be further compromised by loss of habitat structure. Unless benthic communities can recover between disturbances, there will be a steady decline in the structural complexity of the reef, with corresponding declines in the abundance of fishes that use the reef for shelter. Some species, such as territorial herbivores and invertebrate feeders, may initially increase in abundance as coral cover declines, but even these species will decrease in abundance if habitat structure erodes. Declines in species richness and abundance will be highly patchy, and interspersed with cycles of recovery, but the overall trend will be negative if climate change continues to cause severe and repeated impacts on the composition and physical structure of the reef benthos.

Range expansions and contractions of GBR fishes will likely occur as ocean temperature increases. Some northern range fish species will extend their southern distribution limits as temperature increases. A smaller number of southern range species will contract their northern distribution limits as temperatures increases. Some of these southern endemic species will face an increased risk of extinction from other threats as their ranges contract. Range extension and contractions are unlikely to have significant consequences for the productivity of most fisheries species. An exception is *Lethrinus miniatus* (sweetlip or redthroat emperor), which is expected to become more restricted to southern locations as temperature increases. The timing of seasonal migrations by pelagic species will likely shift to match the changed thermal regime. Whether the productivity of pelagic fisheries is impacted will largely depend on the effect that climate change has on ocean productivity and the abundance of smaller prey species.

Increased temperature will probably cause a shift in life history traits of local populations, although these changes will be relatively small compared to the natural variation already exhibited by many species across their geographic ranges. The most likely response to rising temperatures will be a shift in life history traits in southern populations to more closely match those currently seen in northerly locations. We predict there will be a trend towards populations of fishes breeding earlier, breeding over a longer period, and having reduced maximum size and longevities compared to current day populations.

Climate induced changes to oceanographic conditions could have far-reaching consequences for the growth, survival, and dispersal patterns of larval fishes, with important implications for the dynamics of adult populations[31]. However, predictions of how ocean currents and productivity patterns will change on the GBR over the next 50 to 100 years lack sufficient certainty to formulate conclusions about the impacts on fish populations. This is a critical gap in our knowledge of climate change impacts on the GBR.

Small increases in ocean temperature (1 to 2°C) may be beneficial for the supply of new recruits to adult populations. However, temperature changes at the upper range of climate change predictions (3 to 4°C) are likely to have negative effects on the reproductive performance of adults, especially if they are combined with the predicted extremes of ocean acidification. The overall conclusion is that small increases in temperature might not be harmful, and could even be beneficial to larval growth and survival, but larger increases are likely to have significant consequences for the replenishment of fish populations. These predictions need to be weighed against the considerable stochastic variation that occurs in larval supply through time and space.

It seems likely that many fish species will acclimatise to increased sea temperature as a result of existing phenotypic plasticity in their populations. Connectivity between populations should promote genetic adaptation to temperature by gene flow from extant populations in warmer conditions. Genetic adaptation to climate change over the next 50 to 100 years will be most evident in small, short-lived species, where selection can operate over a large number of generations. Some reef fishes live for many decades and we do not expect to see strong genetic adaptation to changing climate over the next 50 to 100 years in these species, unless there is extensive gene flow from low latitude populations. There is little prospect of significant genetic adaptation to habitat degradation. Habitat loss could have a negative effect on the potential for adaptation to other environmental changes, because adaptation will be slower in populations that have been reduced in size and that have lower connectivity as a result of habitat degradation.

Throughout this review we have tried to provide a framework for understanding the likely consequences of climate change for fishes on the GBR. We stress that confidence in many of our conclusions is low because of: i) uncertainty in climate change projections; ii) poor understanding of the responses likely to accompany changes in environmental factors at individual, population and community levels; and iii) the complexity of interactions that can occur between the different physical and biological factors that will be affected by climate change and their interactions with other coral reef stressors.

### 12.6.2 Potential management responses

Although there is little prospect of controlling climate change in the short to medium future, linking management strategies that target other human impacts such as exploitation and sedimentation may increase the resilience of reef habitats[75]. Given the evidence for top-down control of coral reefs, maintaining healthy predator and herbivore fish populations may provide a certain amount of resilience to climatically induced changes. However, marine protected areas are not a 'catch-all' solution to the problems faced by coral reefs, and ultimately, they cannot protect biodiversity from extrinsic disturbances[19,85]. While marine protected areas can benefit exploited species when habitat is degraded, it must be recognised that the majority of small reef fish species are not exploited and are more likely to be influenced by habitat degradation than exploitation. Enhancing reef resilience by maintaining water quality and limiting disturbances that stress corals and degrade reef habitat will be critical for maintaining healthy assemblages of reef fishes.

There are formal management regimes in place for commercially targeted fish stocks on the GBR, making them relatively well protected compared to most other reef regions. It will be important to ensure stocks are well managed into the future to reduce the risk of fisheries collapses as the effects of climate change become more pronounced. Ensuring that GBR fisheries have fully implemented ecosystem-based fishery management regimes in line with recently developed national standards will be important for maintaining sustainable stocks and ensuring fisheries productivity. Integrating potential impacts of climate change into this framework is a critical next step. Incorporating a 'safety

margin' into harvest levels could also provide some insurance in the face of uncertainty about the impacts of climate change. Consideration should also be given to the possibility that reduced planktonic productivity and loss of benthic shelter could lead to a reduction in food supply for pelagic and reef-based fisheries species. Harvest levels may need to be adjusted if there are substantial reductions in the abundance of smaller prey species.

Mangroves, estuaries and wetlands are important nursery and juvenile habitats for some GBR fishes. These habitats are under increasing threat from terrestrial development in addition to the potential impacts associated with climate change, and require additional protection to prevent their continued loss or degradation. The consequences of installing barriers to mitigate sea level rise needs to be considered carefully because these devices can restrict key ontogenetic movements of fish between coastal wetlands, estuaries and the sea.

### 12.6.3 Further research

A great deal more research is required before we can predict the full ramifications of climate change for fishes on the GBR. More information is required on the effects that changes in the physical environment (eg temperature and pH) will have on the function and behaviour of reef fishes. Nearly all the available data on how fishes respond to changes in these environmental factors comes from temperate species and these results might not be directly applicable to tropical marine fishes. Improved projections of how productivity on the GBR will change as a result of climate change will also be critical for understanding how individual performance and population dynamics will respond to changes in the physical environment.

Regional models of ocean circulation on the GBR under various climate change scenarios are required to assess the impacts of climate change on dispersal patterns of marine animals, including fishes. Oceanographic models will also be critical for predicting the spatial and temporal patterns of planktonic productivity on the GBR under different climate change scenarios. Once we have these predictions, we also need reliable estimates of the scales of dispersal and retention exhibited by fish larvae on the GBR. Only then can models be parameterised with meaningful estimates of larval growth, survival and dispersal, and applied in sensitivity analyses to assess the potential impact of climate change on the replenishment of adult populations.

More information is needed on the habitat requirements of reef fishes, especially around the time of settlement. Many reef fishes are closely associated with live coral habitat at the time of settlement, even if adults are not. This may explain why a range of species have been observed to decline in abundance following large-scale losses of live coral. Understanding the habitat requirements of fishes throughout their life will enable more precise predictions to be made about the long term consequences of declining coral cover for reef fish assemblages.

Finally, more attention needs to be given to the potential for acclimation and adaptation of reef fishes to a changing climate. Ultimately, it is the potential for species to adapt to a changing climate that will set the boundaries for future population characteristics and geographical distributions.

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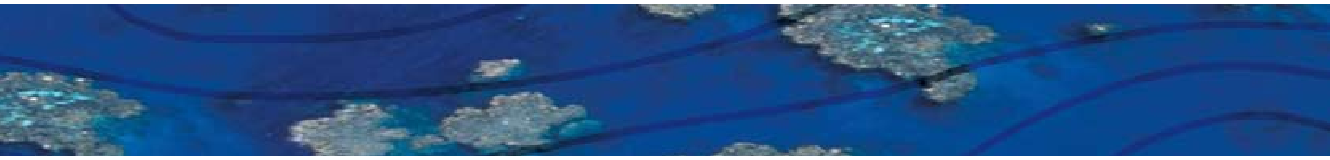

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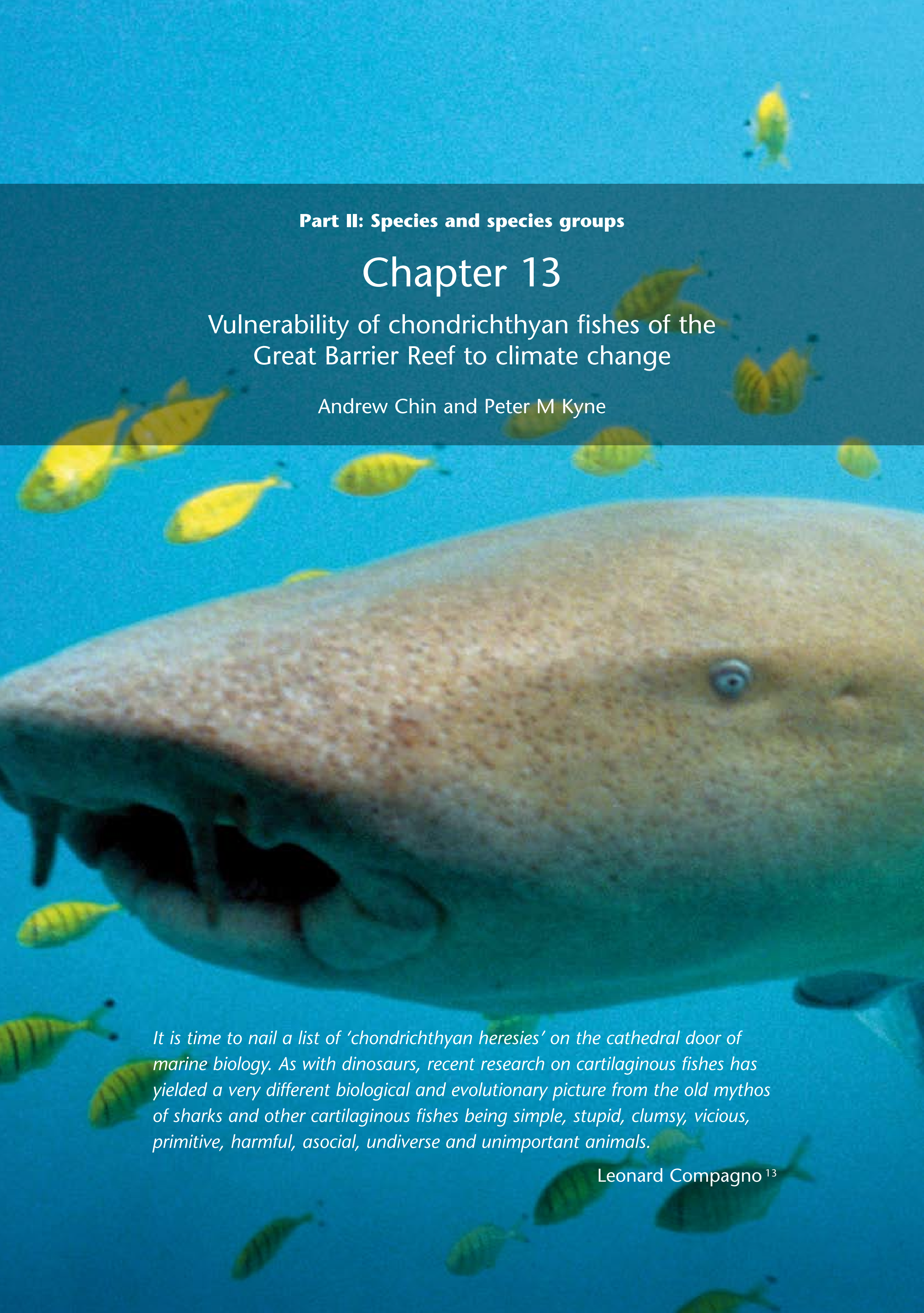


**Part II: Species and species groups**

# Chapter 13

## Vulnerability of chondrichthyan fishes of the Great Barrier Reef to climate change

Andrew Chin and Peter M Kyne

> *It is time to nail a list of 'chondrichthyan heresies' on the cathedral door of marine biology. As with dinosaurs, recent research on cartilaginous fishes has yielded a very different biological and evolutionary picture from the old mythos of sharks and other cartilaginous fishes being simple, stupid, clumsy, vicious, primitive, harmful, asocial, undiverse and unimportant animals.*
>
> Leonard Compagno[13]

## 13.1 Introduction

This chapter addresses the potential impact of climate change on the chondrichthyan fauna of the Great Barrier Reef, that is, the sharks, rays, skates and holocephalans that occur within the Great Barrier Reef region. The terms 'sharks and rays' or 'sharks' are used throughout this chapter to describe this diverse group of fishes.

Relatively little is known about the sharks and rays of the Great Barrier Reef (GBR), and research has been sporadic and patchy. We have collected information from a variety of sources including unpublished data to assemble a baseline of understanding on what climate change may mean for the sharks of the GBR. This assessment provides predictions about how climate change may affect these animals. These predictions rely on information contained in other chapters about climate change and its impacts on the habitats and biological processes of the GBR ecosystem.

We have used a semi-quantitative method to assess the vulnerability of sharks and rays to climate change, and our approach is modelled on methods used to assess the ecological risk of many animals, including sharks and rays, in fisheries. The intent is to use a clear and logical process to assess the vulnerability of the various species and groups of sharks and rays to predicted climate change scenarios over the next 100 years. Whereas this assessment is restricted to the sharks and rays of the Great Barrier Reef, it is hoped that this process will be of use in assessing the potential impacts of climate change on species in other regions.

### 13.1.1 Chondrichthyan fishes

The chondrichthyan fishes are more commonly known as sharks, rays, skates and holocephalans. These fishes have skeletons made of light and flexible cartilage instead of bone. This separates them from the bony fishes (the teleosts) such as coral trout and salmon.

Sharks and rays have been present in the Earth's oceans for about 400 million years, and in that time have been a highly successful group of vertebrates. Today approximately 1200 species of sharks and rays occur in habitats ranging from tropical coral reefs to Arctic waters, and freshwater rivers to deep sea habitats of the continental slope and beyond[5,14]. Australia has a diverse range of sharks and rays with around 300 species recorded, half of which are found nowhere else in the world[40]. The sharks and rays of the tropical waters of northern Australia have one of the highest levels of diversity and endemism in the world[40,39,48]. The GBR also contains a diverse range of shark and rays with 134 species recorded from the region[35,36,40]. This chapter considers all species found within the GBR, as well as those occurring in adjacent habitats, that is, the deepwater and freshwater environs that are interconnected with the GBR ecosystem. Sharks and rays occur in all GBR habitat types with a handful of species also occupying freshwater habitats on the GBR coast[38].

#### *13.1.1.1 Life history strategies*

Sharks have very different life history traits compared with teleost fishes and have evolved K-selected life histories (Figure 13.1). This means that sharks have reproductive strategies geared towards producing a small number of well-developed young that have high survival rates. In this context, shark populations have characteristics similar to marine mammals such as dolphins, and are especially vulnerable to human impacts[5]. Compared to most bony fishes, sharks:

- are relatively slow growing and long-lived
- generally take a long time to reach sexual maturity
- reproduce slowly and produce few young
- have fewer natural enemies and higher survival rates[5,29].

In general, these life history traits mean that adult sharks are relatively hardy (low adult mortality rates), and many sharks are able to tolerate a wide range of environmental conditions. However, the low reproductive rate also means that adaptation through evolutionary change is relatively slow. Present groups of sharks appeared in the Jurassic and Cretaceous periods between 245 and 65 million years ago, and have not undergone significant evolutionary change since.

***Figure 13.1*** *Compared to bony fish, sharks live for a long time, grow slowly and produce few young. As a group, they have relatively slow rates of evolutionary change and are sensitive to intense human pressures. Once depleted, shark populations can take considerable time to recover.*

This reproductive strategy also makes sharks vulnerable to unnaturally high levels of adult mortality. A K-selected life history strategy means that the number of young produced is closely linked to the number of breeding adults. Thus, as the number of adult sharks declines, the number of new recruits entering the population may also decline. As a result, shark populations can be reduced relatively quickly and once depleted, may take a long time to recover. For example, demographic analyses of sawfish populations in the western Atlantic suggest that even if effective conservation measures are introduced, recovery of these populations could take several decades[64].

## 13.1.2 Ecology, significance and values of chondrichthyan fishes in the GBR

### *13.1.2.1 Ecological roles*

All sharks are predatory and as a group feed on a wide variety of prey. In general, smaller benthic dwelling sharks may feed primarily on crustaceans, molluscs and other invertebrates, whereas reef sharks and more open water species prey primarily upon fishes. Species such as whale sharks, *Rhincodon typus*, and manta rays, *Manta birostris*, are specialists that feed on plankton[86]. Sharks live in a variety of habitats, ranging from nearshore environs and coral reefs to open water pelagic environments and benthic habitats of the continental shelf, slope and beyond. Many species found in the GBR move between different habitats at various stages of their life cycle, using habitats such as estuaries and seagrass beds as nurseries or foraging grounds[3,26,65,74].

Their wide distribution and consumption of a diverse range of prey mean that sharks perform important roles in the GBR ecosystem[56,61,73]. Many sharks are higher-level predators[86], and ecosystem models suggest that in this role, sharks may help to regulate populations of prey species and maintain ecosystem balance. For example, removing tiger sharks, *Galeocerdo cuvier*, from model simulations caused seabird populations to increase as there were fewer tiger sharks consuming seabirds. This led to increased predation by seabirds on fishes, and ultimately led to the collapse of some fish populations[75]. Research on the diet of tiger sharks suggests that they may play a role in regulating populations of marine turtles and dugongs[66]. Nevertheless, specific 'cause and effect' relationships linking sharks and other marine organisms are difficult to demonstrate. Although it is likely that sharks exert significant influence on other marine organisms, it is difficult to predict what changes might occur should sharks be removed from an ecosystem[75].

#### *13.1.2.2 Ecological groupings*

The large number of species of sharks and rays makes it difficult to discuss their ecology on a species by species basis. However, this discussion can be greatly simplified by organising the species into discrete groups based on habitat use, anatomy, ecology and lifestyle. While these sorts of groupings can be developed in a number of ways[13], habitat use is usually a key factor in defining these groups.

This chapter divides the GBR's 134 species of sharks and rays into six discrete units called functional groups. Each functional group is based on the different habitat zones found between the coast and the deep waters of the continental slope. Each habitat zone consists of a number of specific habitats (eg seagrass beds). A species is included in a functional group if it *primarily* occurs in the habitats found in that zone, and is affected or dependent in some way upon the physical, chemical and ecological processes occurring in those habitats. Species lists for each functional group were developed directly from published information on species distribution and habitat use[35,36,40], unpublished data provided by contributing authors (Terence I Walker, Rory B. McAuley, John D Stevens, Christine L Dudgeon and Richard D Pillans) and others (W White pers comm), or inferred from published literature on the same or similar species from other regions. The six functional groups are described below.

- **Freshwater and estuarine** (4 species) – Habitats include rivers and streams, inter-tidal zones of estuaries and bays, mangroves and salt marsh, intertidal seagrass beds, foreshores and mudflats.
- **Coastal and inshore** (47 species) – Habitats extending from coastal sub-tidal habitats to the mid-shelf platform or ribbon reefs. Includes estuaries and bays, sub-tidal seagrass beds, inshore fringing reefs, shallow coastal waters, rocky shoals, sponge gardens and other benthic habitats of the GBR lagoon to 30 metres depth.
- **Reef** (19 species) – Habitats on and immediately adjacent to mid-shelf and outer-shelf coral reefs, down to a maximum depth of 40 metres in the GBR lagoon and to 60 metres on outer shelf reefs.
- **Shelf** (26 species) – Deeper water and seabed habitats between the mid-shelf and outer reefs, extending to the continental slope edge. Includes waters from the surface to 200 metres (approximately the shelf edge) and benthic habitats such as deepwater seagrass beds and *Halimeda* mounds, rocky shoals and sponge gardens (40 to 60 metres depth).

- **Bathyal** (54 species) – Benthic habitats of the continental slope and beyond, extending down to 2000 metres depth.
- **Pelagic** (10 species) – Open ocean waters extending from the edge of the outer reefs and beyond into the Coral Sea.

Highly mobile and ecologically 'flexible' species such as the bull shark, *Carcharhinus leucas*, commonly occur in more than one habitat type and thus appear in more than one functional group. In contrast, more sedentary and less 'flexible' species such as the freshwater sawfish *Pristis microdon* are restricted to particular habitats and are only listed in one functional group.

Functional groups are generalisations and while there may be overlap between groups, they have been developed to provide a manageable framework for assessing the vulnerability of GBR sharks and rays to climate change.

### 13.1.2.3 Social, cultural and economic significance

The sharks and rays of the GBR have significant social, cultural and economic values. Sharks and rays are of great social and cultural importance to indigenous communities of the GBR coast and Torres Strait. Several indigenous groups consider sharks as cultural icons and totems, and sharks and rays are pivotal characters in many dreamtime stories. The act of fishing is an important social activity and rays are an important source of food for many indigenous communities[12,43,68].

Sharks and rays are also valuable as dive attractions in the A$6.1 billion GBR tourism industry. Surveys of SCUBA divers visiting the GBR found that sharks were rated as the top attraction that divers most wanted, and most expected, to see[45]. The economic value of sharks as living attractions has been documented outside Australia. Research in the Maldives found that a single grey reef shark, *Carcharhinus amblyrhynchos*, generated US$33,500 per year at the most popular shark watching dive site, and was worth on average US$3,300 per year across all shark watching dive sites. In the Caribbean, the tourism value of a single live Caribbean reef shark, *Carcharhinus perezi*, has been estimated at between US$13,300 and US$40,000 per year[1]. The income generated by shark ecotourism has prompted increased awareness and community education about shark conservation, and provides economic benefits for both the tourism industry and local communities[1].

Sharks are also taken as target species and bycatch in the Queensland East Coast Inshore Finfish Fishery[58,63]. The pressure on sharks in the GBR has increased since 1990, with more specialist shark fishers entering the gillnet fishery and more effort being directed at targeting sharks[59]. Commercial fishery logbooks have recorded a significant increase in reported shark catch and effort in the net fishery in the GBR, rising from 295 tonnes from 191 boats in 1994 and peaking at 1202 tonnes from 221 boats in 2003[53]. Estimates of targeted shark fishing effort (as the percentage of fishing days targeting shark) increased by 28 percent over the same period meaning that fishers have shifted effort to target sharks[59]. The total Gross Value of Production derived from sharks taken from the GBR net fishery has risen accordingly, from A$1.97 million in 1988, peaking at A$7.21 million in 2003[53]. Since 2003, both the number of boats and catch have declined with 150 boats landing 634 tonnes in 2005. This follows the buyout of 59 active net licenses under a structural adjustment package following rezoning of the Great Barrier Reef Marine Park[53,54]. However, there are still significant concerns regarding the fishery, including the long-term sustainability of the take of sharks and rays[16].

## 13.1.3 Status of chondrichthyan fishes in the Great Barrier Reef

There is little information available about the status and trends of shark populations on the GBR[10]. The most extensive set of data are contained in catch records reported in commercial fisheries logbooks. However, logbooks only record the combined catch of all shark and ray species and thus cannot be used to assess the status and trends of individual species. Long-term fishery-independent surveys of shark populations on the GBR have not been conducted. Smaller-scale research surveys are ongoing, but at this time, they are limited in duration and coverage.

There are conservation concerns for several species of sharks and rays in the GBR and 19 species are listed as threatened (Critically Endangered, Endangered or Vulnerable) by the International Union for Conservation of Nature and Natural Resources in the 2006 *IUCN Red List of Threatened Species*[33]. The grey nurse shark, *Carcharias taurus*, Bizant river shark, *Glyphis* sp. A and all four species of sawfish occurring in the GBR region are listed as Critically Endangered. Additionally, recent research has revealed significant declines in populations of whitetip reef shark, *Triaenodon obesus*, and grey reef shark, *Carcharinus amblyrhynchos*, on the GBR[57]. Formal assessment of the conservation status of these species in the GBR using the IUCN Red List Categories and Criteria is underway and will likely reveal conservation concern for these reef sharks (W Robbins pers comm).

The conservation status of sharks on the GBR is of concern to marine managers due to increases in reported catch and the general lack of information available on population trends[10]. This is especially relevant given the inherent vulnerability of sharks and rays to fishing pressure and the poor sustainability record and documented collapse of many shark fisheries around the world[4,82].

## 13.1.4 Climate change factors affecting chondrichthyan fishes

Sharks and rays may be affected by a large number of physical, chemical and ecological factors that influence their immediate environment or affect the habitats, food webs and ecological interactions upon which they depend. Consequently, the climate change scenarios and ecological processes described in other chapters of this volume form the basis of our understanding of how climate change may affect sharks and rays. Relevant chapters include those on species groups (marine microbes, plankton, mangroves, seagrass, corals, benthic invertebrates and fishes), and habitats and processes (reefs, pelagic, coastal and estuarine, physical oceanography and coral reef resilience).

A review of this information revealed that there are ten climate change drivers most likely to affect sharks and rays. These drivers may alter environmental conditions resulting in direct physiological effects, or may affect habitats and ecological processes that indirectly affect sharks and rays. The assessment considers changes and impacts predicted over the next 100 years.

### Direct links between climate drivers and GBR sharks and rays

Three climate change drivers were identified as *directly* affecting the physiology of sharks and rays.

### *13.1.4.1 Sea and air temperature*

### *Projected increase in sea temperature of 1 to 3°C, projected increase in air temperature of 4 to 5°C by 2100*

The majority of GBR sharks and rays are ectothermic and changes in environmental temperature will affect physiological processes such as metabolic rates[7]. Most ectothermic fishes favour habitats that have a suitable temperature range. Temperature may also influence behaviour, and tracking studies have shown that sharks will feed in warmer waters and rest in cooler waters[42]. Changes in temperature driven by climate change may result in changes in metabolism, behaviour and movement patterns. Sharks may move to new areas where optimum temperatures exist (see section 13.1.6), however, research into thermal tolerances for some estuarine and benthic species has indicated that they can tolerate a wide range of temperatures[18,30,81]. Predicted increases in temperature of 1 to 3°C may be greater in shallow freshwater, estuarine, coastal and inshore habitats and reef flat lagoons during low tide, than in the shelf, bathyal and pelagic environments.

Increased temperature will also result in lower dissolved oxygen concentrations in the water. This could increase the possibility of respiratory stress as rising temperature results in decreased dissolved oxygen levels and increased metabolic rates. However, at least one species of shark (epaulette shark, *Hemiscyllium ocellatum*) has demonstrated the ability to tolerate these conditions[72], and some species show reduced activity and metabolic rates in response to lower oxygen levels[7]. Consequently some sharks may be able to tolerate lower levels of dissolved oxygen.

There is little evidence that the occurrence or severity of disease in sharks has changed due to anthropogenic factors including climate change[37]. However, future increases in temperature may increase the incidence of disease by facilitating the spread of warm-water parasites and increasing their growth rates and reproductive output[37].

### *13.1.4.2 Ocean acidification*

### *pH decrease of 0.4 to 0.5 by 2100*

The acid/base (pH) balance in sharks and rays is tightly regulated and they can compensate for acidity changes by rapid pH buffering[17]. The gills are the main organ that balances pH in sharks and rays. Sharks and rays are found in a wide range of environments and pH regimes, but the effects of environmental pH on the physiology and behaviour are not well understood. Increased ocean acidity could lead to increased energy costs as sharks and rays work harder to maintain an optimum pH balance.

### *13.1.4.3 Freshwater input*

### *Increased salinity extremes due to greater rainfall variability (more intense droughts and floods)*

During the tropical monsoon, the GBR receives pulses or flushes of fresh water from floods created by heavy rain in coastal catchments. Climate change may increase rainfall variability, resulting in greater extremes of flood and drought. Prolonged droughts with reduced freshwater inputs may increase salinity in some intertidal and sub-tidal environments, especially in closed or impounded waters, and cause freshwater ponds to dry up. Increased temperature and evaporation may further increase salinity extremes, and reduce dissolved oxygen levels (see section 13.1.4.1). Floods will reduce salinity and may wash pollutants from the catchment into coastal habitats. The greatest changes in salinity are likely to occur in freshwater, estuarine and coastal habitats.

Some sharks and rays can tolerate a wide range of salinity regimes and may even be predominantly found in freshwater environments[7,38]. Experiments show that some sharks and rays can tolerate decreased salinity, but that this may result in increased energy costs to maintain the correct osmotic balance[7]. Similarly, some sharks and rays can tolerate increases in salinity by retaining more salts such as urea in their blood[51,79]. However, the impacts of long-term salinity changes on sharks and rays are not well understood.

### Indirect links between climate drivers and GBR sharks and rays

Seven climate change drivers were identified as *indirectly* affecting sharks and rays in the GBR. These large-scale drivers affect the condition and availability of critical habitats, or may alter ecological processes that regulate the abundance and distribution of prey.

Some sharks use particular habitat types such as shallow seagrass meadows or estuarine habitats for nursery grounds where young can find food and seek shelter from predators. Adult sharks may use certain habitat types to find food and shelter, to mate or give birth. There is also increasing evidence of philopatry that may strengthen the reliance of some sharks on particular habitats and locations[31].

Some species (eg the whale shark) rely on certain prey while others are able to exploit a wide range of prey species. The movement of highly migratory, plankton feeding species such as whale sharks have been correlated with the availability of plankton (see section 13.1.6). Pelagic species may rely on a biological calendar; events such as turtle nesting, seabird fledging or aggregations of prey such as baitfish shoals to influence their movements.

### *13.1.4.4 Oceanographic impacts*

### *Changes in East Australian Current bifurcation point, currents and upwellings linked to the El Niño Southern Oscillation*

The East Australian Current (EAC) is the main current affecting the GBR, but the reefs and island chains create local eddies and jets. Climate change could cause the bifurcation point of the EAC to move south (Steinberg chapter 3). Increased current strength may lower thermoclines and reduce the strength of upwelling currents. Upwellings of nutrient rich cooler water occur off outer shelf reefs, for example around the Swains Reefs. The input of nutrients allows for the growth of plankton and thus, forms the basis of marine food webs in these areas.

Climatic changes expressed through changes in El Niño events can alter these currents and upwellings and thus, alter prey availability, migration patterns and the timing of specific events such as baitfish aggregations or plankton blooms. Migration patterns of whale sharks in Western Australia have been linked to plankton blooms and currents associated with El Niño[80,87]. In addition, El Niño and upwellings have been linked to significant changes in prey availability that caused collapses in fisheries and seabird populations (Kingsford and Welch chapter 18, Congdon et al. chapter 14).

### *13.1.4.5 Water and air temperature*

### *Projected increase in water temperature of 1 to 3°C, projected increase in air temperature of 4 to 5°C by 2100*

Increased temperature will increase the frequency and severity of coral bleaching events, and potentially increase bio-erosion. This could lead to long-term losses of coral habitats, particularly of corals such as *Acropora* that create the complex structure of the coral reef that provides habitat for many reef

fishes. Up to half of the species of reef fish, important prey for some sharks and rays, could decline if coral cover is decreased (Munday et al. chapter 12). Increased temperature would also increase the incidence of seagrass 'burning' leading to habitat loss for both sharks and their prey. Losses would be greater in coastal and shallow reef seagrass habitats (Waycott et al. chapter 8). Temperature can affect nutrient cycling in microbial communities and plankton with flow-on effects to marine food webs (Webster and Hill chapter 5, McKinnon et al. chapter 6).

### *13.1.4.6 Sea level rise*

### *Sea level rise of 0.1 to 0.9 metres by 2100*

Increasing sea level will have significant effects on coastal habitats. Rising sea level will increase salinity in estuaries and the lower reaches of creeks and rivers, and alter geophysical processes of erosion and deposition along the coastal zone. Mangroves may decline in some areas but expand in regions such as the Fitzroy Basin by replacing salt marsh and freshwater wetland habitats. However, physical barriers such as human structures may prevent migration landward. The loss of salt marshes and wetlands could have significant effects on prey species. Sea level rise would also drive seagrasses landward and lead to expansion in some areas, but again physical barriers and mangroves could restrict migration landward. In other areas, seagrasses could become 'squeezed' between deeper water and barriers (such as established mangrove forests) and decline. Impacts on rivers, wetlands, mangroves, salt marshes, seagrasses, estuaries, mudflats and beaches will alter the availability of these habitats to sharks and rays, and any prey that also rely on these habitats[11] (Waycott et al. chapter 8, Lovelock and Ellison chapter 9, Sheaves et al. chapter 19).

### *13.1.4.7 Severe weather*

### *Increased frequency and intensity of severe storms and cyclones*

Increases in destructive storms and cyclones will have significant impacts on immobile organisms and habitats, especially in shallow waters. Storms can generate destructive winds and waves that physically damage habitats, or lead to erosion and deposition of large amounts of material that alter hydrology and the physical landscape. More intensive storms result in increased levels of damage, and increased frequency of storms means that habitats and communities have less time to recover between storm events. Habitat loss will occur when the frequency and intensity of severe weather events exceeds the habitat's ability to recover from one event to the next. Habitats most at risk from severe weather include shallow habitats such as wetlands, mangroves, seagrasses and coral reefs. Many sharks and rays, and/or their prey, rely on these habitats for shelter or food. Seagrass and mangrove habitats are also critical nursery grounds for a number of species and loss of these habitats could have significant impacts on population growth and recovery of prey. Severe storms may also affect the movement and behaviour of some sharks[28].

### *13.1.4.8 Freshwater input*

### *Increased variability in rainfall regimes leading to greater extremes of droughts and floods*

Increased extremes of drought and flood can result in increased extremes of salinity that lead to stress in marine communities such as seagrass beds and coral reefs. Floods and associated decreased salinity have resulted in significant loss of seagrasses (Hervey Bay) and coral reefs (Keppel Islands) in the past. Increased flood activity may increase the amount of pollutants reaching coastal habitats and mid-shelf reefs. Severe droughts will reduce freshwater input into catchments and reduce the availability of freshwater habitats. Prolonged droughts can make plant communities more vulnerable to diseases and pests, lead to mortality and cause long-term changes in community composition. Wetlands, mangroves, seagrasses and coral reefs are important habitats to sharks and rays and their prey.

The productivity of freshwater, estuarine, coastal and inshore systems may be closely linked to rainfall, with higher rainfall triggering increased abundance of prawns and crabs, and influencing the reproduction of fishes such as barramundi[11,44,46,70]. Increased variability in rainfall and freshwater input may decrease the stability of coastal food webs and cause greater extremes of prey availability (Kingsford and Welch chapter 18, Sheaves et al. chapter 19).

#### *13.1.4.9 Light and ultra-violet radiation*

#### *Increased levels of light and ultra-violet (UV) radiation linked to El Niño events*

During El Niño events, cloud cover and wave action are reduced which allows greater penetration of ultraviolet (UV) radiation through the water column. Increased levels of UV radiation may alter the community composition of microbial communities with effects on nutrient cycling and productivity of key habitats. Higher levels of UV radiation have detrimental effects on some larval fish. Increased light intensity may damage some seagrasses and is an important contributing factor in coral bleaching. It is not known how much climate change will affect light and UV radiation levels and subsequently impact GBR inhabitants (Waycott et al. chapter 8, Hoegh-Guldberg et al. chapter 10, Munday et al. chapter 12, Fabricius et al. chapter 17).

#### *13.1.4.10 Ocean acidification*

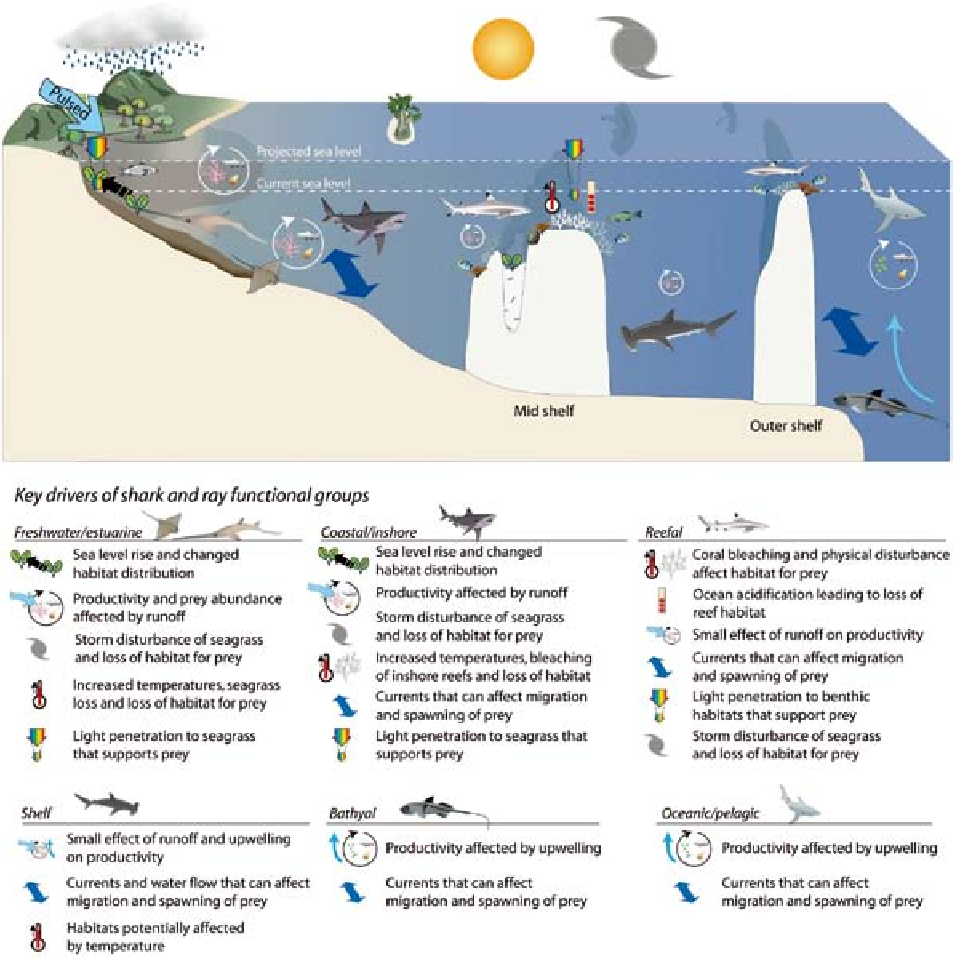
#### *pH decrease of 0.4 to 0.5 by 2100*

Ocean acidification has been included as a large-scale driver for the reef functional group only. The potential effects of ocean acidification on coral reefs have been explored and literature suggests that increased acidity predicted by climate change scenarios could lead to significant degradation of coral habitats (Hoegh-Guldberg et al. chapter 10). While increased ocean acidification may reduce skeletal development in some marine organisms, the effects of ocean acidification on sharks and rays, or on the vast majority of habitats and ecological processes in the GBR are not well understood. Ocean acidification has not been considered in the assessment of the other five shark and ray functional groups.

### 13.1.5 Climate change drivers and functional groups

Sharks and rays of the GBR depend upon a variety of habitats and ecological processes, and these dependencies differ according to the functional group. For example, the health of seagrass beds may have a significant effect on sharks in the coastal and inshore functional group, whereas sharks in the pelagic functional group are more dependent on currents and upwellings. The habitats, key processes and dependencies of each functional group, and the interaction of climate change drivers with these processes, are summarised in Figure 13.2.

***Figure 13.2*** *Six functional groups of sharks and rays and the main climate change drivers that may affect the habitats and biological processes upon which they depend*



## 13.1.6 Documented impacts of climate change on sharks and rays in the GBR and elsewhere

There are no published assessments on the impacts of climate change on any of the sharks and rays found in the GBR. Indeed, there is little information available on the topic anywhere in the world. However, there has been considerable focus on the effects of climate warming on marine communities in the north Atlantic[60,69] and a handful of studies have included references to chondrichthyan species[50,52,71]. Alterations in community structure, together with biogeographical shifts of calanoid copepods and fish communities in the northeast Atlantic has been correlated with increasing northern hemisphere temperature and the North Atlantic Oscillation[2,50,52].

In the northeast Atlantic, increasing water temperature has been advantageous to subtropical fish species that have wide latitudinal ranges, while the abundance of temperate and more narrow-ranging species have decreased[52], with many species displaying shifts in mean latitude or depth over extended time periods[50]. In the Bay of Biscay, numbers of the temperate spiny dogfish, *Squalus acanthias*, declined from 1973 to 2002, which Poulard and Blanchard[52] related to climate change. They also documented changes in the abundance of the cuckoo ray, *Leucoraja naevus*. However, it may be more difficult to isolate the effects of ocean warming from those of historically high fishing pressure (targeted and bycatch) on both of these species in the northeast Atlantic. Perry et al.[50] did however, show latitudinal and depth shifts in both exploited and non-exploited marine fish species. They demonstrated a shift in mean depth for the cuckoo ray related to temperature, with the species moving into deeper water as a response to ocean warming. Three chondrichthyan species examined (cuckoo ray, spiny dogfish and the small spotted catshark, *Scyliorhinus canicula*) did not display latitudinal shifts related to climate warming[50].

Quero[55] reported on the northward extension of the distributions of tropical fish species, and Stebbing et al.[71] linked warming of the North Atlantic with the immigration of warmer-water species to the Cornish coast of England. For the period of 1960 to 2001, the increasing number of records of southern species was significantly correlated with rises in temperature[71]. The analysis included the first record of the sharpnose sevengill shark, *Heptranchias perlo*, for the British Isles and the first record of the tropical to warm-temperate bigeye thresher, *Alopias superciliosus*, for Cornwall.

It has been theorised that some pelagic shark species may be detrimentally affected by climate change due to the role temperature plays in determining seasonal distribution and abundance. Seasonal aggregations of whale sharks off Western Australia have been weakly correlated to sea surface temperature and this parameter has been shown to be highly correlated with the abundance of basking sharks, *Cetorhinus maximus*, off southwest Britain[15,87]. Whale sharks are known to aggregate at certain times to feed on plankton blooms associated with coral spawning[80]. The loss of coral reefs or disruption of coral spawning could have significant impacts on these animals. Stewart and Wilson[77] suggested that coral bleaching events, which are related to increasing water temperatures, and rapid climate change are amongst the greatest threats to whale sharks.

## 13.2 Vulnerability of GBR sharks and rays to climate change

A standardised framework for assessing the vulnerability of habitats, taxa and ecological processes to climate change was described in chapter 1. This framework uses three 'components', *exposure, sensitivity* and *adaptive capacity* to derive vulnerability to climate change drivers. Exposure and sensitivity are 'negative' components that describe the potential impacts of climate change. The higher the exposure or sensitivity, the greater the vulnerability to climate change. Adaptive capacity is a 'positive' component that describes an organism or habitat's ability to accommodate change. A high adaptive capacity will reduce vulnerability to climate change. This chapter assesses these three components and integrates them using an approach used in fisheries ecological risk assessments (see section 13.2.4).

The method used to assess vulnerability to climate change is intended to be clear and logical, and follows a progression of clearly defined steps:

1. Ranking the exposure (low, moderate, high) of each functional group to the ten climate change drivers identified
2. Identifying the biological *attributes* of sharks and rays that direct their response to climate change drivers. These attributes define their sensitivity and adaptive capacity
3. Ranking each attribute of sensitivity and adaptive capacity as low, moderate or high, for each species to each of the climate change drivers
4. Multiplying the rankings for exposure, sensitivity and adaptive capacity to derive a vulnerability assessment for each species in each functional group
5. Collating the individual species rankings into an overall assessment of the vulnerability of each functional group

### 13.2.1 Exposure

Exposure is a 'negative' component with high exposure equating to increased potential impact from climate change. Ten of the climate change drivers identified in chapter 2 were identified as being relevant to sharks and rays of the GBR. These drivers may affect the physiology of sharks and rays by altering the immediate physical and chemical environment, or affect the large-scale ecosystem processes (eg habitat quality or abundance of prey) upon which sharks depend. Physiological drivers exert direct pressure on sharks, whereas large-scale processes affect other parts of the ecosystem that in turn have indirect flow-on effects on sharks.

Exposure to a specific climate change driver depends on two factors:

- the extent to which the species' geographic and depth range overlaps with the climate change driver; and,
- the extent to which the climate change driver effects the habitats and ecological processes upon which the species depend.

To identify the key processes and habitats likely to be affected by the ten climate change drivers published literature, chapter 2 and the other chapters in this volume were used. This list was compared with the functional group descriptions to rank exposure (low, moderate or high) of each group. For example, if the majority of habitat types in a functional group were highly likely to be severely affected by sea level rise, the functional group would be assessed as having high exposure to that climate change driver.

### 13.2.2 Sensitivity

Sensitivity is a 'negative' component where high sensitivity equates to increased potential impact from climate change. The sensitivity of a species to a climate change driver depends on its ability to resist or adapt to change. However, attributes that define sensitivity can also be considered as factors that provide a species with the ability to adapt to change – adaptive capacity. For example, sensitivity to increasing temperature can also be defined as a species' capacity to adapt to warmer conditions. Consequently, this chapter treats sensitivity as attributes of a species that it cannot easily change, whereas attributes linked to its ability to change or adapt are considered as attributes of adaptive capacity. Sensitivity is defined by two attributes:

- *Rarity:* A rare species has a small population and may lack genetic variation. Smaller populations are more sensitive to pressures as they have fewer individuals or 'chances' to cope with climate change drivers. Secondly, their lower abundance means a lower net reproductive output. This reduces the species' ability to recover from climate change related mortality. This is especially important in sharks and rays that, as a group, have conservative life history characteristics. Rare species have high sensitivity.
- *Habitat specificity:* Some sharks and rays may be restricted to a particular habitat as these provide the species with necessary resources such as suitable prey or refuge from predators. These species may not be able to compete effectively in other habitats whereas more flexible species are able to exploit alternative habitats should one habitat type be adversely affected. Species with high habitat specificity have high sensitivity.

Sensitivity to each climate change driver was ranked as low, moderate or high. This ranking was based on literature and unpublished data about the rarity and habitat use of these species.

### 13.2.3 Adaptive capacity

Adaptive capacity is a 'positive' component that describes a species' ability to acclimate or accommodate change. High adaptive capacity means that a species is able to more readily accommodate change, which reduces the potential impacts from climate change drivers. Accommodation may occur where physiological or behavioural responses result in acclimation or compensation that allow the species to be successful in the new conditions. This is the opposite of the other two components of vulnerability (exposure and sensitivity), which are 'negative' components and the higher they are, the greater the potential impact.

In order to integrate the three components (exposure, sensitivity and adaptive capacity) in the assessment framework all three components need to be expressed as 'negative' terms. Hence, the attributes of adaptive capacity need to be expressed as levels of *inadaptability*. For example, if a species has physiological traits that allow it to tolerate a wide range of temperatures, it is ranked as having *low* inadaptability, which is the equivalent of saying that it has a *high* adaptive capacity.

Inadaptability is defined by four attributes:

- *Trophic specificity:* species that depend on specific types of prey are less adaptable. If certain types of prey become unavailable, these sharks and rays may not be able to exploit alternative prey types. Such species have high inadaptability. An example would be the whale shark that feeds exclusively on plankton. Species that feed on a wide range of prey items may shift feeding patterns to exploit alternative prey. These species have a low inadaptability. For example, tiger sharks feed on a larger variety of prey and are better able to switch feeding preferences.
- *Physical or chemical intolerance:* some species have physiological traits that allow them to tolerate a wide range of physical and chemical conditions such as salinity or temperature. These species are better able to accommodate changing conditions. For example, the bull shark can tolerate a wide range of salinities and would be ranked as having low inadaptability.
- *Immobility:* some sharks and rays have the ability to move between different areas to exploit favourable conditions[30]. Immobile species are incapable of travelling large distances

(morphological restrictions) or cannot overcome physical barriers that prevent them from reaching new areas. For example, a species living on isolated seamounts is 'immobile' if it cannot reach another seamount. This species would be assessed as having high inadaptability.

- *Latitudinal range (proxy for temperature intolerance):* some species of sharks and rays are found over large latitudinal ranges and thus inhabit a wide range of temperature regimes. This infers that these species have the capacity to be successful in a wide range of temperatures. This attribute is particularly important, as there is little information available on the temperature tolerances of the vast majority of sharks and rays found in the GBR.

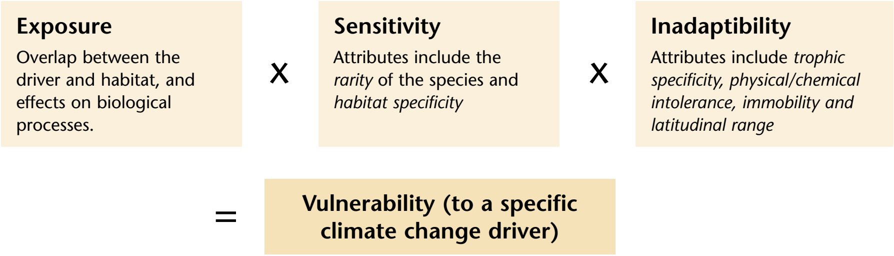
The inadaptability of each species was ranked as low, moderate or high. This ranking was based on literature and unpublished data on these species.

### 13.2.4 Assessing the vulnerability of shark and ray species

Chapter 1 provides a framework for assessing vulnerability that combines the three components exposure, sensitivity and adaptive capacity. In this chapter, the framework has been adapted to risk assessment techniques developed for sharks and rays in Australian fisheries that provide semi-quantitative assessments[23,78,84,85]. Fisheries ecological risk assessment frameworks use terms such as *availability, encounterability* and *selectivity,* that relate to exposure, and the term *post-release mortality* that relates to sensitivity. This semi-quantitative approach has the advantage that each component is clearly defined and rated using a standard assessment, and that the overall assessment is transparent. If required, interested parties can identify the individual attributes of a species that have resulted in it being assigned a specific vulnerability ranking.

The fisheries risk assessment multiplies the individual component ratings together to produce a final outcome that describes the risk to that species. This chapter uses the same approach as the fisheries risk assessment[85], where each component is individually rated and then multiplied to derive overall vulnerability. The level of exposure, sensitivity or inadaptability is rated as 0.33 (low), 0.66 (moderate) or 1.00 (high). These ratings are multiplied together to derive vulnerability that is expressed as a proportion ranging from 0.00 to 1.00, where 0.00 to 0.33 equals low vulnerability, 0.34 to 0.66 equates to moderate vulnerability, and 0.67 to 1.00 equates to high vulnerability. This is demonstrated in the equation in Figure 13.3.

**Figure 13.3** *Integration of the three components of climate change to calculate vulnerability*



**Exposure**
Overlap between the driver and habitat, and effects on biological processes.

X

**Sensitivity**
Attributes include the *rarity* of the species and *habitat specificity*

X

**Inadaptibility**
Attributes include *trophic specificity, physical/chemical intolerance, immobility and latitudinal range*

=

**Vulnerability (to a specific climate change driver)**

The multiplicative approach is generally conservative and most calculations will result in scores of less than 0.33 (Table 13.1). For example, if a species has high sensitivity and high inadaptability to a climate change driver but is unlikely to ever encounter the driver (low exposure), then overall vulnerability to that driver is low. In contrast, a species will only be assessed as being highly vulnerable when all three components of vulnerability are high (Table 13.1). This is logical because for a species to be highly vulnerable to climate change, it has to be highly exposed *and* have high sensitivity *and* be highly inadaptable. For example, a highly sensitive species that was highly exposed to a climate change driver may not be especially vulnerable *if* it had the ability to rapidly adapt to the change and continue to be successful (low inadaptability).

This framework applies several assumptions and logical rules:

- It is assumed that all climate change drivers, attributes and components of vulnerability are equally significant. For example, temperature has the same significance as severe weather, rarity is as significant as habitat specificity or exposure is as significant as sensitivity.
- When assessing a species' sensitivity or inadaptability, the highest ranking of any of the attributes is used. For example, if a species is very abundant (low rarity = low sensitivity) but is restricted to a single specific habitat type (high habitat specificity = high sensitivity), overall sensitivity is ranked as high. In this case, it doesn't matter how many individuals there are because if that habitat is lost, the impact on all individuals of the species will be high.
- A mathematical consequence of this approach is that when exposure, sensitivity and inadaptability are all moderate, the calculated vulnerability is low (0.66 X 0.66 X 0.66 = 0.29 = low). In this situation vulnerability is arbitrarily assessed as moderate.
- If there is no information available to assess the sensitivity or inadaptability of an attribute, it is ranked as high. This applies the precautionary principle where the lack of information increases risk. This is especially relevant to sharks and rays given their conservative life history characteristics.

***Table 13.1*** *Calculated outcomes of combinations of vulnerability ratings*

| | Sensitivity x inadaptability | | | | | |
|---|---|---|---|---|---|---|
| **Exposure** | L*L | L*M | L*H | M*M | M*H | H*H |
| H | 0.11 | 0.22 | 0.33 | 0.44 | 0.66 | 1.00 |
| M | 0.07 | 0.14 | 0.22 | 0.29# | 0.44 | 0.66 |
| L | 0.03 | 0.07 | 0.11 | 0.14 | 0.22 | 0.33 |

# this is ranked as moderate following logical rules (see above)

It should be noted that vulnerability rankings are specific for the GBR region. For example, a temperate species may occur in a wide range of latitudes that extends north into the GBR. Warming in the GBR could alter the range of this species southwards and out of the GBR region. In this scenario, vulnerability would be assessed as high as the species would be 'lost' from the GBR ecosystem, even though it continued to occur in regions south of the GBR.

Many sharks and rays are able to move considerable distances compared with other species. High mobility imparts an additional complication in this assessment and while mobility is assessed as an

attribute of 'adaptive capacity', little is known about the capacity to migrate or the present movement patterns of GBR sharks and rays, or indeed how some species might alter their behavioural patterns or habitat use in response to climate change.

### 13.2.5 Vulnerability assessment results

#### 13.2.5.1 Significance of the ten climate change drivers to sharks and rays

- The most significant climate change driver is temperature as all functional groups have either high or moderate exposure to the direct and/or indirect impacts of increasing temperature.
- Freshwater input and/or ocean circulation are significant drivers for most functional groups. These drivers affect ecosystem productivity and could result in changes to prey availability. Freshwater input affects functional groups closer to the coast while ocean circulation affects the bathyal and pelagic functional groups.
- Sea level rise and severe weather are significant drivers for the freshwater and estuarine, and coastal and inshore functional groups. Rising sea level may result in significant losses of critical estuarine, mangrove and seagrass habitats, and the ecosystem services they provide.
- Exposure to the direct affects of ocean acidification was assessed as low for every functional group. Consequently, every species was assessed as having low vulnerability to direct physiological effects from ocean acidification. Ocean acidification as an indirect, large-scale driver was only assessed for the reef functional group, which had high exposure to this driver.

#### 13.2.5.2 Exposure of each functional group to climate change drivers

Exposure rankings for each functional group are given in Table 13.2. Exposure to each climate change driver varied in response to the habitats and key dependencies and linkages of each group (see Figure 13.2 for review).

- Species in the freshwater and estuarine functional group have the highest exposure of all functional groups, with high exposure to seven of the nine relevant climate change drivers. There are clear links between climate change drivers and most of the key habitats and ecological processes upon which these species depend.
- Species in the coastal and inshore functional group have high exposure to climate change drivers. Many of the habitats and ecological processes that these species depend on are likely to be affected by climate change.
- Species in the reef functional group have high to moderate exposure to climate change drivers. Exposure is through potential declines and loss of coral reefs via increased stresses such as coral bleaching. Ocean acidification has particular implications for coral reefs and was considered in the assessment of the reef functional group.
- Species in the shelf and pelagic functional groups have low to moderate exposure. Few of the climate change drivers are likely to affect habitats and ecological processes that these species depend on.
- Species in the bathyal functional group had the lowest exposure. Most climate change drivers are unlikely to affect these deepwater habitats.

***Table 13.2*** *Exposure of each functional group to the physiological (direct) and large-scale (indirect) climate drivers. Exposure (as a component of vulnerability) assessed as low (L), moderate (M) or high (H)*

| **Driver** | | **Functional Group** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **Freshwater and estuarine** | **Coastal and inshore** | **Reef*** | **Shelf** | **Bathyal** | **Pelagic** |
| **Physiological (direct)** | Temperature | H | H | H | M | M | M |
| | Ocean acidification | L | L | L | L | L | L |
| | Freshwater input | H | M | M | M | L | L |
| **Large-scale (indirect)** | Ocean circulation | L | M | M | H | M | H |
| | Temperature | H | H | H | M | L | L |
| | Sea level rise | H | H | L | L | L | L |
| | Severe weather | H | H | H | L | L | L |
| | Freshwater input | H | H | M | M | L | L |
| | Light | H | M | M | L | L | L |
| | Ocean acidification | – | – | H | – | – | – |

Drivers: Temperature (water and air temperature); Ocean acidification (pH decrease); Freshwater input (rainfall, freshwater input, floods and drought); Sea level rise (sea level rise and coastal inundation); Severe weather (cyclonic disturbance and severe weather events); Light (UV).

* Increased ocean acidification is a large-scale driver with particular implications for reefs and has been assessed for this functional group only.

### *13.2.5.3 Vulnerability of species and functional groups to climate change*

The vulnerability assessment framework produced vulnerability rankings (low, moderate or high) for each species in each functional group, for each of the climate change drivers. The assessment produced more than 50 tables of results that are available for request via the editor (J Johnson). These tables include:

- Results tables showing the calculation of vulnerability rankings for each species in each functional group to each of the climate change drivers (55 tables in total)
- Summary tables showing the exposure of each functional group, the sensitivity and inadaptability ranking of each species in each functional group, and the resulting vulnerability to each climate change driver (one table for each functional group – six tables in total)

The vulnerability results for each functional group are summarised in Table 13.3. The main patterns and trends emerging from these results are presented below.

The vulnerability of each functional group to a specific climate change driver depends on the vulnerability rankings of each species within the group. For example, if the majority of species within a functional group have low vulnerability to sea level rise, the overall vulnerability of the functional

group to sea level rise is described as low. Similarly, the overall vulnerability of a functional group to climate change (the sum of all the climate change drivers) depends on the vulnerability of the group to each of the climate change drivers. For example, if a functional group has low vulnerability to seven climate change drivers, it is described as having a low overall vulnerability to climate change (Table 13.3).

These results only consider vulnerability to climate change drivers. The interaction between human activities and climate change drivers, and the potential synergies arising from these interactions are considered in section 13.3.2.

### *Freshwater and estuarine functional group (4 species):* moderate *vulnerability to climate change*

- Species in this group had high exposure to all climate change drivers except for ocean acidification and ocean circulation (Table 13.2). The climate change drivers identified may lead to habitat loss, and cause changes in freshwater input that affect biological productivity and food webs.
- The freshwater whipray *Himantura* cf. *chaophraya* is the most vulnerable species in this group. It is a relatively rare species, and has high habitat and trophic specificity. As species in this group are exposed to the highest number of climate change drivers, the freshwater whipray is potentially the most vulnerable chondrichthyan on the GBR to climate change.
- Three of the four species in this group have high sensitivity (are rare and live in specific habitats). However, these species are adapted to relatively harsh conditions and thus have moderate to low inadaptability (ie they are able to adapt to changing conditions). This compensates for their high exposure and sensitivity.
- This results in an assessment of low or moderate vulnerability for three of the four species in this group, producing a group ranking of moderate vulnerability to climate change (Table 13.3).

*Other considerations:*

- Adaptive capacity is founded on the principle that these species are able to move to and successfully exploit new areas should conditions in their existing habitats deteriorate. This assumption is untested and should be treated with caution.

### *Coastal and inshore functional group (47 species):* low *vulnerability to climate change*

- Species in this group had high to moderate exposure to climate change drivers (Table 13.2). The most significant drivers were temperature, sea level rise, severe weather events, and changes in freshwater input that can affect biological productivity and food webs.
- The porcupine ray *Urogymnus asperrimus* has high vulnerability to climate change due to its rarity and immobility, and the high to moderate exposure of this group to climate change drivers.
- The sawfishes of the family Pristidae, stingrays (Dasyatidae), eagle rays (Myliobatidae), stingarees (Urolophidae), butterfly rays (Gymnuridae) and cownose rays (Rhinopteridae) had low to moderate vulnerability to climate change. Attributes contributing to the assessment of species as moderately vulnerable included rarity, habitat and trophic specificity and immobility.

- The whaler sharks (Carcharhinidae), weasel sharks (Hemigaleidae) and hammerhead sharks (Sphyrnidae) had low sensitivity and inadaptability (ie high adaptive capacity) resulting in a ranking of low vulnerability to climate change.
- Overall, approximately 70 percent of species in the coastal and inshore group had low vulnerability and over 27 percent had moderate vulnerability to the nine climate change drivers assessed for this group (Table 13.3).
- The group was assessed as having an overall low vulnerability to climate change (Table 13.3).

### *Reef functional group (19 species):* low to moderate *vulnerability to climate change*

- The reef functional group had high to moderate exposure to most climate change drivers (Table 13.2). Temperature, severe weather and ocean acidification were the most significant climate change drivers due to their potential impacts on habitat.
- Species in this group have low to moderate vulnerability to climate change. None of these species were identified as having high vulnerability.
- Species assessed as being moderately vulnerable to climate change included some stingrays (Dasyatidae), longtail carpet sharks (Hemiscylliidae), the tawny nurse shark, *Nebrius ferrugineus*; zebra shark, *Stegostoma fasciatum*; and grey nurse shark, *Carcharias taurus*. These species tended to have moderate habitat specificity and/or immobility.
- Close to 70 percent of these species have a moderate or high dependency on coral reef habitats.
- Species in this group are also generally flexible and can tolerate a range of environmental conditions, have low to moderate trophic specificity and most species are relatively abundant.
- Overall, vulnerability for this group is low to moderate as they generally have high adaptive capacity that counteracts their reliance on specific habitat (Table 13.3).

*Other considerations:*

- Habitat specificity requires highlighting for sharks and rays inhabiting coral reefs. These species tend to have moderate to high habitat specificity and high exposure, but are relatively flexible and thus have low inadaptability (high adaptive capacity). As in the freshwater and estuarine group, it is assumed that reef sharks and rays will be able to move to and successfully exploit new habitats and resources. Coral reefs have narrow environmental tolerances and this habitat type is considered especially at risk to climate change. The assumption that reef sharks and rays will be able to move to unaffected reefs or locate other habitats that provide the same ecosystem services as coral reefs is untested and should be treated with caution.

### *Shelf functional group (26 species):* low *vulnerability to climate change*

- Species in this group had low to moderate exposure to climate change drivers (Table 13.2). Temperature, ocean circulation and freshwater input were the most significant climate change drivers due to their potential impacts on biological productivity and food webs.
- Twenty-six percent of the species in this group had moderate vulnerability. These species are from a wide range of families but all shared moderate to high rarity and/or limited latitudinal ranges (a proxy for temperature intolerance).

- Most of the other species in the shelf functional group are relatively abundant and widespread, and are relatively flexible, feeding on a wide variety of prey and occurring in a variety of habitats and locations. Consequently they were assessed as having low vulnerability to climate change.
- Some species are only moderately mobile which may reduce their ability to adapt to changing conditions.
- Low to moderate exposure, low sensitivity and low inadaptability for most species gave this group an overall ranking of low vulnerability to climate change (Table 13.3).

*Other considerations:*

- Little is known about the habitats, biodiversity and ecological processes occurring in the shelf habitats. This introduces more uncertainty in the assessment of this group and highlights the need for more research in these habitats.

### *Bathyal functional group (54 species):* low *vulnerability to climate change*

- Species in this group had low exposure to climate change drivers with the exception of ocean circulation (moderate) and temperature (moderate) (Table 13.2).
- These species have low habitat specificity but many are relatively rare (high sensitivity).
- Bathyal species exploit a variety of prey and can potentially tolerate a range of environmental conditions, but are moderately immobile.
- Low exposure combined with low to moderate inadaptability results in a group assessment of low vulnerability to climate change (Table 13.3).

*Other considerations:*

- The habitats, biodiversity and ecological processes occurring on the continental slope and beyond are poorly known. For example, some species may potentially be present in larger numbers but surveys of bathyal habitats are lacking. While changing rarity from ‘high’ to ‘low’ would not affect the outcome of this vulnerability assessment, it highlights the need for more research in these habitats.

### *Pelagic functional group (10 species):* low *vulnerability to climate change*

- Species in this group had low exposure to climate change drivers except for ocean circulation (high) and the direct effects of temperature change (moderate) (Table 13.2).
- The devil rays (*Manta birostris, Mobula thurstoni* and *M. eregoodootenkee*) and whale shark *R. typus* are the most vulnerable species in this group as they are plankton feeding specialists, and the whale shark and bentfin devil ray, *M. thurstoni*, are relatively rare. However, these species have low exposure to most climate change drivers so are ranked as having low overall vulnerability to climate change.
- All species in this group have low habitat specificity and low inadaptability (they are flexible species) with the exception of plankton feeding specialists.
- The low exposure and inadaptability give this group vulnerability rating of low (Table 13.3).

***Table 13.3*** *Vulnerability to the physiological and large-scale climate-change drivers by percentage of species within each functional group. Vulnerability assessed as low (L), moderate (M) or high (H). Numbers in parentheses are numbers of species*

| **Driver** | | **Functional Group** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **Freshwater and Estuarine (4 species)** | **Coastal and Inshore (47 species)** | **Shelf (26 species)** | **Reef (19 species)** | **Bathyal (54 species)** | **Pelagic (10 species)** |
| **Physiological** | **Temperature** | 25.0% H (1)<br>50.0% M (2)<br>25.0% L (1) | 2.1% H (1)<br>27.7% M (13)<br>70.2% L (33) | 0.0% H (0)<br>23.1% M (6)<br>76.9% L (20) | 0.0% H (0)<br>47.4% M (9)<br>52.6% L (10) | 0.00% H (0)<br>63.0% M (34)<br>37.0% L (20) | 0.0% H (0)<br>40.0% M (4)<br>60.0% L (6) |
| | **Ocean acidification** | 100% L (4) | 100% L (47) | 100% L (26) | 100% L (19) | 100% L (54) | 100% L (10) |
| | **Freshwater input** | 25.0% H (1)<br>50.0% M (2)<br>25.0% L (1) | 0.00% H (0)<br>29.8% M (14)<br>70.2% L (33) | 0.0% H (0)<br>23.1% M (6)<br>76.9% L (20) | 0.0% H (0)<br>47.4% M (9)<br>52.6% L (10) | 100% L (54) | 100% L (10) |
| **Large-scale** | **Ocean circulation** | 100% L (4) | 0.00% H (0)<br>29.8% M (14)<br>70.2% L (33) | 3.9% H (1)<br>19.2% M (5)<br>76.9% L (20) | 0.0% H (0)<br>47.4% M (9)<br>52.6% L (10) | 0.00% H (0)<br>63.0% M (34)<br>37.0% L (20) | 20.0% H (2)<br>20.0% M (2)<br>60.0% L (6) |
| | **Temperature** | 25.0% H (1)<br>50.0% M (2)<br>25.0% L (1) | 2.1% H (1)<br>27.7% M (13)<br>70.2% L (33) | 0.0% H (0)<br>23.1% M (6)<br>76.9% L (20) | 0.0% H (0)<br>47.4% M (9)<br>52.6% L (10) | 100% L (54) | 100% L (10) |
| | **Sea level rise** | 25.0% H (1)<br>50.0% M (2)<br>25.0% L (1) | 2.1% H (1)<br>27.7% M (13)<br>70.2% L (33) | 100% L (26) | 100% L (19) | 100% L (54) | 100% L (10) |
| | **Severe weather** | 25.0% H (1)<br>50.0% M (2)<br>25.0% L (1) | 2.1% H (1)<br>27.7% M (13)<br>70.2% L (33) | 100% L (26) | 0.0% H (0)<br>47.4% M (9)<br>52.6% L (10) | 100% L (54) | 100% L (10) |
| | **Freshwater input** | 25.0% H (1)<br>50.0% M (2)<br>25.0% L (1) | 2.1% H (1)<br>27.7% M (13)<br>70.2% L (33) | 0.0% H (0)<br>23.1% M (6)<br>76.9% L (20) | 0.0% H (0)<br>47.4% M (9)<br>52.6% L (10) | 100% L (54) | 100% L (10) |
| | **Light** | 25.0% H (1)<br>50.0% M (2)<br>25.0% L (1) | 0.00% H (0)<br>29.8% M (14)<br>70.2% L (33) | 100% L (26) | 0.0% H (0)<br>47.4% M (9)<br>52.6% L (10) | 100% L (54) | 100% L (10) |
| | **Ocean acidification** | NA | NA | NA | 0.0% H (0)<br>47.4% M (9)<br>52.6% L (10) | NA | NA |
| **Overall group vulnerability** | | **Moderate** | **Low** | **Low** | **Low to moderate** | **Low** | **Low** |

Red text highlights the vulnerability ranking that accounts for the majority of the species in the functional group. Blue text highlights where two vulnerability rankings are evenly represented amongst the majority of species in that functional group. NA = not applicable . Number in brackets represents number of species within each functional group within that category

*Other considerations:*

- The oceanographic and ecological processes driving the pelagic environments of the outer reef and Coral Sea are not well understood. This introduces more uncertainty in the assessment of this group and highlights the need for more research in these habitats.
- Many of these species are highly migratory and travel between oceans. These species may rely on a biological 'calendar of events' that affects their migration and movement patterns. The biological events that these species rely on may be significantly affected by global climate change, but have not been considered in this assessment.

## 13.3 Linkages

### 13.3.1 Linkages between sharks and rays and marine ecosystems

Sharks and rays occupy ecological niches at the upper levels of marine food webs, and are thus closely linked to many other parts of the marine ecosystem. Changes occurring in habitats, or in biological processes operating at lower levels of the food web, can cause a chain of events that ultimately affect sharks and rays.

The effects of climate change on these habitats and processes are considered in other chapters of this volume, specifically chapters on species groups (marine microbes, plankton, mangroves, seagrass, coral reefs, invertebrates and fishes), and on habitats and processes (reefs, pelagic and coastal and estuarine, physical oceanography and coral reef resilience). The main linkages between these habitats and processes and sharks and rays are outlined below.

Many sharks and rays may have specific habitat requirements and use certain habitats as foraging grounds, breeding grounds or to provide shelter from predators. Seagrass beds, mangroves and other estuarine habitats are important breeding and nursery grounds for a number of sharks[8,26,65]. Many species such as tiger sharks and whaler sharks also use these habitats as foraging grounds (eg (Blaber et al.[3], Heithaus et al.[26]). Habitats may be particularly important at certain stages in the life cycle of sharks and rays. For example, juvenile sharks have been found to use nursery grounds to avoid predators, which increases survival rates of young sharks[27,67]. There is also increasing evidence of philopatry in some sharks and rays. These species repeatedly return to the same habitats in specific locations at different times in their life cycle to mate, give birth or feed[31]. This increases their dependency on particular habitats in specific locations.

Habitats also provide food and shelter for many prey species and the degradation or loss of these habitats may decrease the availability of suitable prey. Seagrasses and mangroves are important habitats for other marine species such as fishes, crustaceans, marine turtles and marine mammals[6,9,49]. In some cases, coastal habitats are linked to coral reefs offshore. For example, the diversity and abundance of reef fish may be linked to the presence of coastal mangroves[47]. Some reef fishes rely on particular types of coral for food or shelter. Corals also create a complex structure similar to trees in a forest, creating habitat for a great diversity of marine species that sharks and rays prey upon. The loss of coral reef habitat may result in declines in half the reef's species of teleost fishes (Munday et al. chapter 12).

Changes to ecological processes may also have indirect impacts on sharks and rays by altering prey availability. In coastal and estuarine ecosystems, biological productivity (the process where physical elements are cycled into biomass) and nutrient cycling are closely linked to photosynthesis by marine plants and the activity of microbial communities. These processes create edible food (plants and micro-organisms) that forms the foundation of many marine food webs that drive the availability of prey. Physical processes such as freshwater runoff, currents and upwelling also affect biological productivity[11]. For example, the abundance of prawns and fishes such as barramundi are correlated with rainfall and river flow[46,70]. In pelagic and bathyal ecosystems, biological productivity is linked to upwelling currents that bring nutrients into these ecosystems. These nutrients feed plankton that in turn, are consumed by many marine organisms that sharks and rays ultimately prey upon.

### 13.3.2 Constraints to adaptation

Chondrichthyan fishes have existed in various forms for some 400 million years and have evolved life history traits that have allowed them to be highly successful over evolutionary time. However, these same traits (long lived animals with relatively low mortality rates and reproductive outputs) mean that sharks and rays evolve very slowly[41], and are unlikely to be able to adapt to changing conditions over the next 100 years through evolutionary processes. Furthermore, climate change is occurring at unprecedented rates making it more unlikely that sharks will be able to adapt through evolution. It is more likely that sharks will adapt to climate change by changing their behaviour, distribution and exploiting new opportunities. This will alter the patterns of abundance and distribution observed today[83]. In the GBR, species that are able to tolerate and exploit warming conditions will likely expand their ranges south, a pattern that has already been observed in marine ecosystems elsewhere (see section 13.1.6). However, sharks and rays that are unable to tolerate warming conditions, or are unable to compete with the influx of northern species, will retreat southwards and may be lost from the GBR.

It should be noted that while chondrichthyans have survived mass extinction events over evolutionary time, the number of species of sharks and rays present today is significantly less than the shark and ray diversity evident in fossil records[24]. Consequently, the extinction of even a few species of modern sharks or rays represents a significant loss to global chondrichthyan diversity.

Many sharks and rays are assessed as having low vulnerability to climate change because they have low inadaptability. These sharks are able to compensate for the impacts of climate change through physiological responses, by moving away from adverse conditions, feeding on alternative prey or finding and successfully establishing themselves in alternative habitats. The capacity for physiological adaptation is determined by the biological traits of each species, but the capacity for sharks to move and exploit alternative prey or habitats depends on these alternative habitats and prey being available. This is especially relevant for reef species as coral reefs require a narrow band of environmental conditions and thus, only thrive in specific locations.

### 13.3.3 Synergies between climate change and other pressures

#### *Existing pressures*

The pressure from human activities such as fishing may increase vulnerability of a range of marine species to climate change[52]. Around the world sharks and rays are under increasing pressure from fishing and habitat loss and significant declines in many shark populations have been recorded[5,76,83]. Their conservative life history traits (see section 13.1.1) mean that human pressures can cause, and have caused the removal of large numbers of sharks in relatively short time periods, resulting in the collapse of these populations. Once depleted, it may take decades for shark populations to recover[64]. The reduction of shark populations, and subsequent reduction in reproductive output, may reduce the capacity of shark populations to absorb or recover from climate change impacts

In the GBR, human pressures on sharks and rays are increasing[10] and some sharks and rays in the GBR are threatened with extinction. The catch of sharks and rays in commercial fisheries, mostly coastal and inshore species, has increased four-fold since 1993[53]. Fishing pressure may have also driven population declines in reef species such as grey reef and white tip reef sharks, which have experienced declines of over 80 per cent on some reefs[57].

Coastal habitats on the GBR such as seagrass meadows, inshore reefs and mangroves are also under increasing pressure. Coastal development such as expansion of urban centres, aquaculture, agriculture and the infrastructure associated with these developments (roads, ports, causeways etc), have led to significant changes in coastal areas. Impacts may be caused by land clearing or reclamation, modifying catchments through dams and weirs, changing water flows and coastal hydrology, and the input of pollutants such as pesticides and nutrients that can poison organisms or cause algal blooms that disrupt marine ecosystems[25,32]. While large-scale destruction of wetlands, mangroves, seagrasses and other habitats has not occurred in recent times, localised losses have been recorded. Furthermore, the extent to which these habitats have been altered since European settlement in the 1800s is unknown[20]. Degradation of these habitats may result in loss of critical nursery or foraging grounds for sharks and rays, and affect the availability of prey. These sorts of impacts add to the effects of climate change.

The immediate concern is the current mortality and sustainability of these populations, and the protection of their habitats. The potential impacts of climate change should be considered in management strategies addressing these pressures.

#### *Future pressures*

The likely human responses to climate change are difficult to predict and are examined in chapter 23 (Fenton et al. chapter 23). The following scenarios are speculative and are based on observations of human modifications to the environment currently evident in the GBR and around the world.

Human responses to climate change may increase existing pressures. Rising sea levels may result in the construction of levees and barriers to prevent flooding. These structures could further disrupt freshwater flows, hydrology and connectivity of coastal habitats such as salt marshes, mangroves and seagrasses[34]. Additionally, these structures could reduce the ability of these habitats to adapt to rising sea levels by colonising suitable areas inland, leading to the loss of these habitats in some areas.

Greater variability in rainfall could prompt the construction of more dams and weirs to store water, and increase pressure on water supplies during droughts. Reduced freshwater flow would reduce the number and size of freshwater pools that provide refuge for aquatic species during droughts, and increase salinity in upper estuarine habitats. Potential increases in catchment modification and water use for human consumption are likely to have significant impacts on estuarine and coastal habitats, ecological processes and biological connectivity which will have flow-on effects for sharks and rays, especially freshwater and estuarine species.

The expansion of deepwater fisheries could have significant impacts on bathyal sharks. Many deepwater sharks and rays are even more vulnerable to fishing pressure, as they are less abundant than other sharks, have even slower growth and reproductive rates[19,84,85], and occur in habitats with relatively low biological productivity. Worldwide, several stocks of deepwater chondrichthyans have already been overfished[21]. Although there is minimal deepwater fishing in the GBR region, the development of such fisheries could have serious consequences for these species and reduce their ability to cope with climate change.

### 13.3.4 Integrating synergies with climate change vulnerability

#### *Freshwater and estuarine, and coastal and inshore sharks and rays*

Coastal habitats (rivers, estuaries, seagrasses and mangroves) are already under significant pressure from human activities. Some inshore coral reefs are showing signs of decline and wetlands and mangroves have experienced localised losses. Future human responses to rising sea levels and greater variability in rainfall may result in increased pressure on freshwater and coastal habitats through the construction of dams or levee banks and impoundment of water. These pressures may increase rates of habitat loss and degradation and disrupt the ecological processes that regulate prey availability.

Freshwater sharks and rays are generally at risk around the world due to their restricted distribution, their proximity to human pressures and the extent of human disturbance to these habitats[38]. Three of the four species in this functional group are listed by the IUCN as threatened with extinction, highlighting the conservation concern for this group. As these species are already facing extinction, additional pressures from climate change could create situations where these species cannot absorb or recover from cumulative impacts, resulting in extinction.

Human impacts on coastal and inshore sharks and rays in the GBR have significantly increased[10]. Given their conservative life history traits, the poor track record of shark fisheries around the world, and the lack of data regarding the sustainability of GBR shark fisheries, these pressures are likely to increase the vulnerability of coastal and inshore sharks to climate change.

There is sufficient evidence to suggest that these additional pressures and synergies will increase the vulnerability of these sharks and rays to climate change. Consequently, the authors conclude that *freshwater and estuarine* species should be considered as **highly vulnerable** to climate change, and the *coastal and inshore group* be considered **moderately vulnerable** to climate change.

### *Bathyal and shelf sharks and rays*

There is little information about the biology, abundance, distribution, and ecological processes that influence sharks and rays found in shelf and bathyal habitats of the GBR. This lack of information is of concern, as this assessment will not have fully considered the exposure to potential climate change impacts. Deepwater species are generally considered to have low growth rates and reproductive outputs, and inhabit environments with low biological productivity. These traits may make bathyal species more vulnerable to climate change, particularly if deepwater currents and upwellings change.

### *Pelagic sharks and rays*

Pelagic sharks and rays are highly migratory species that may encounter significant pressures from both climate change and human activities throughout their range. Many of these pressures are poorly documented and could exert a significant cumulative impact on these species. For example, highly migratory species may encounter multiple fisheries during long distance movements. Highly migratory species may also follow seasonal migration patterns dependant on biological events such as plankton blooms[80]. As climate change is a global phenomenon, climate change impacts may occur throughout the range of these species resulting in a significant cumulative impact. The processes that regulate the movement patterns of many migratory sharks and rays are not well understood, and the impacts of high seas fisheries are poorly documented. Nevertheless, the authors consider that cumulative impacts across the range of these species may be significant, and caution that these pressures may significantly increase the vulnerability of these species to climate change.

## 13.4 Summary and recommendations

### 13.4.1 Major vulnerabilities to climate change

This assessment has highlighted a number of factors that drive the vulnerability of GBR sharks and rays to climate change.

- The potential synergistic impacts of fisheries on sharks and rays in the GBR
- Degradation and loss of coastal habitats such as estuaries, seagrasses and mangroves through climate change impacts and human pressures
- Disruption of ecological processes that drive biological productivity and prey availability by rainfall and oceanographic changes.

Additionally, threatened species and particular species groups (see section 13.2.5.3) may be especially vulnerable to climate change given existing pressures, reduced populations and/or biological attributes.

### 13.4.2 Potential management responses

Under the *Great Barrier Reef Marine Park Zoning Plan 2003*, 33 percent of the Great Barrier Reef Marine Park is zoned as Marine National Park Zones that do not allow extractive activities such as fishing and collecting. These zones protect both habitats and the sharks and rays present within these zones. The joint State and Commonwealth *Reef Water Quality Protection Plan* and Fisheries Habitat Areas declared by the Queensland Government also help to protect coastal and estuarine habitats.

The Queensland Department of Primary Industries and Fisheries (QDPIF) has legislative responsibility for management of Queensland's fisheries. The take of grey nurse sharks, great white sharks and freshwater sawfish is prohibited and shark finning is restricted, but there are few other fisheries regulations that relate specifically to the take of sharks and rays. Structural adjustment of the net fishery in 2004 resulted in the buyout of 59 net licences, reducing both catch and effort. Nevertheless, there are concerns about rising effort in the commercial net fishery and the take of sharks and rays. In 2002, the QDPIF issued an investment warning for the fishery stating that increases in level of catches or fishing effort might not be recognised in future management arrangements. More recently, risk assessments have identified a number of species in the GBR at high risk to fishing[22,62]. Assessments carried out under the *Environment Biodiversity and Conservation Act 1999* have also raised concerns about the long-term ecological sustainability of the fishery. Management arrangements for the Queensland East Coast Inshore Finfish Fishery are currently being reviewed.

In terms of climate change, a number of management actions may potentially reduce the impacts of climate change on sharks and rays in the GBR. These are related to the major vulnerabilities identified.

1) Addressing human activities that contribute to climate change, namely the production of greenhouse gases.
2) Improving fisheries management arrangements for fisheries in the GBR that harvest sharks. Specifically, improving information on the effort, catch (both target and bycatch) and stock assessments for these fisheries to ensure long-term sustainability, especially in the context of impacts from other factors such as climate change.
3) Continuing to protect and preserve critical habitats, particularly freshwater, estuarine, inshore, and reef habitats. This includes preserving the ability of these ecosystems to cope with pressures, including climate change, by protecting these habitats and maintaining the ecological processes that allow them to function.
4) Protect and conserve threatened species, and the species identified in this assessment as being highly vulnerable to climate change.
5) Include vulnerability to climate change in the development of ecological risk assessments for fisheries, assessments of conservation status and the development of conservation and management strategies.
6) Educate communities about the trends, threats and potential impacts of climate change on sharks and rays, and provide them with meaningful ideas on how they could take action to address these impacts.

### 13.4.3 Further research

Relatively little research has been carried out on sharks and rays in the GBR and there is a clear need for more information[16]. Future research could refine and clarify some impacts and vulnerabilities discussed in this chapter. These areas include research to improve the management, conservation and sustainability of sharks and rays to human pressures and research focused specifically on the impacts of climate change on sharks and rays. Key research areas are outlined below.

1) Research to improve the sustainability of fisheries and their impacts on sharks and rays in the GBR. Reducing risks posed by the major human impacts on sharks and rays in the GBR will decrease their vulnerability to climate change. Potential research areas include:
    a) improved information on fishing effort and the composition and amount of catch and bycatch
    b) improved information on the life history, movement and habitat use of key species taken by fisheries in the GBR
    c) development of robust risk assessments, stock assessments and sustainability targets for GBR fisheries that take sharks and rays
    d) ongoing fisheries monitoring to monitor trends in catch and sustainability
2) Research to clarify links between climate change and GBR sharks and rays. This would identify specific dependencies and critical processes that help to inform and prioritise management actions. Potential research areas include:
    a) physiological affects of climate change drivers (eg temperature, pH) on GBR sharks and rays (eg effects on growth, metabolism, reproduction), and the long term consequences of these effects
    b) ecology of key species including movement and habitat use, diet and behaviour, and linkages between these attributes and habitats and processes
    c) mechanisms through which human activities influence these habitats and processes
    d) ecosystem models to refine the predicted impacts of climate change and the cumulative impacts and synergies of climate change and human impacts
3) Research to support the conservation of threatened species and species that are highly vulnerable to climate change including:
    a) life history, movement and habitat use of these species
    b) identification of key threatening processes
    c) monitoring the effectiveness of conservation measures
4) Research to improve knowledge and understanding of the chondrichthyan fauna of the GBR, including:
    a) a comprehensive survey of the chondrichthyan fauna of the GBR to document species and their distribution
    b) taxonomic work to identify and adequately catalogue the diversity of the GBR chondrichthyans

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**Part II: Species and species groups**

# Chapter 14

## Vulnerability of seabirds on the Great Barrier Reef to climate change

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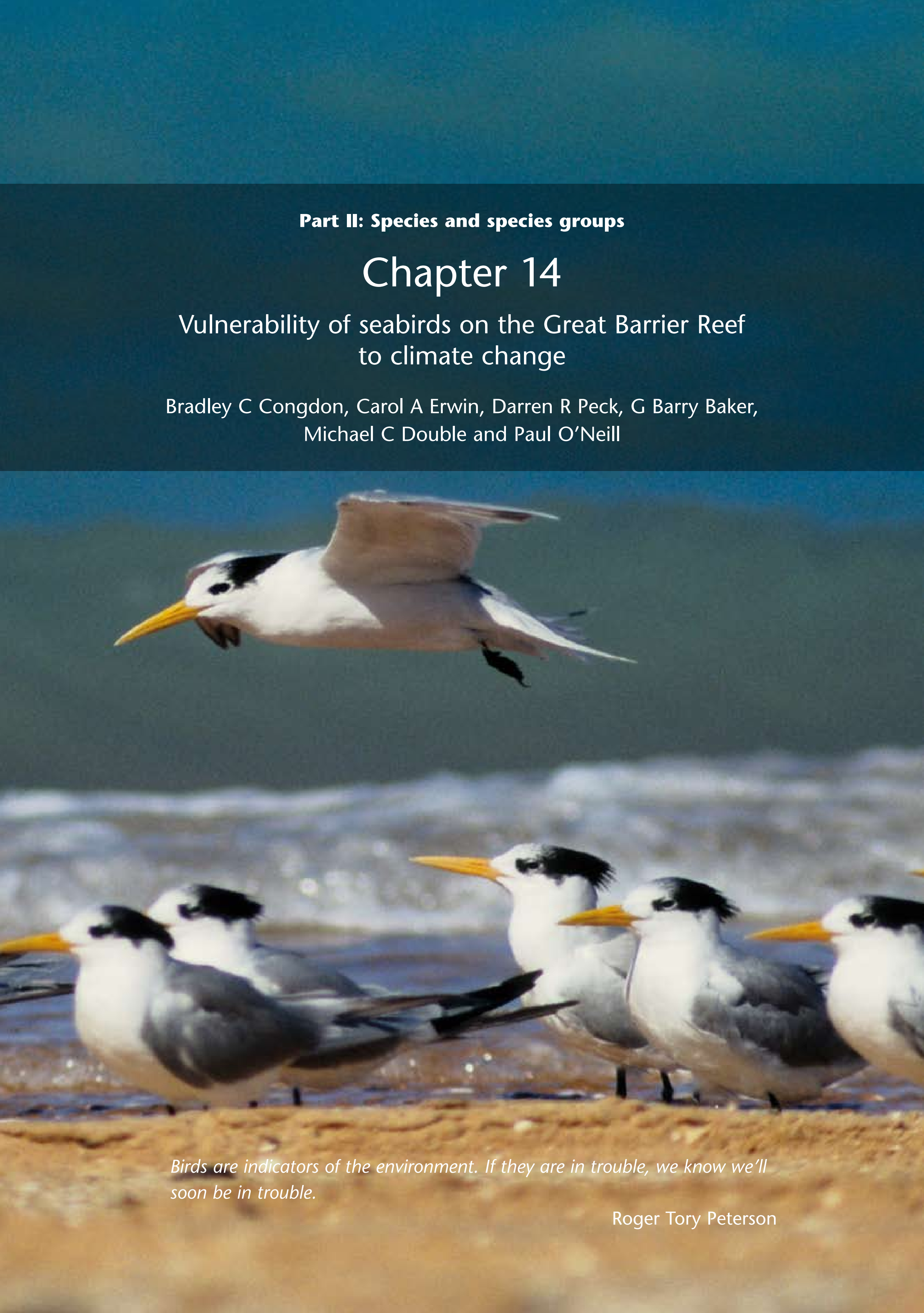

> *Birds are indicators of the environment. If they are in trouble, we know we'll soon be in trouble.*
>
> Roger Tory Peterson

## 14.1 Introduction

Seabirds are highly visible, charismatic predators in marine ecosystems that are defined as feeding exclusively at sea, in either nearshore, offshore or pelagic waters. At a conservative estimate there are approximately 0.7 billion individuals of 309 species of seabirds globally[15]. Such high population abundance means that in all ecosystems where seabirds occur the levels of marine resources they consume are significant[15]. Such high consumption rates also mean that seabirds play a number of important functional roles in marine ecosystems, including the transfer of nutrients from offshore and pelagic areas to islands and reefs, seed dispersal and the distribution of organic matter into lower parts of the developing soil profile (eg burrow-nesting species such as shearwaters)[57].

A total dependence on marine food resources makes seabirds key upper trophic level predators in marine ecosystems… This means that seabird demographics and reproductive parameters are strongly impacted by, and closely reflect, changing oceanographic and trophic conditions. Prey abundance and seabird reproductive biology have been significantly correlated many times (eg Anderson et al.[3], Burger and Piatt[19]). For this reason seabirds are widely considered important indicator species in marine ecosystems[43]. Therefore, understanding how changing oceanographic conditions impact seabird population dynamics and reproductive ecology leads directly to critical insights into the potential future impacts of climate change, not only on seabirds, but on other functionally important components of tropical marine ecosystems.

There are two primary purposes to this chapter. The first is to present and synthesise available information on the sensitivity of seabirds to climate variability at global, regional and local scales, emphasising relationships previously observed in tropical marine ecosystems. This synthesis will then be used to identify the magnitude and scale of resultant impacts attributable to specific climatic/environmental phenomena. When combined with climate change predictions (Lough chapter 2), these findings can be used to identify those climate change processes most likely to affect seabirds of the Great Barrier Reef (GBR) and the potential magnitude and direction of these effects.

Secondly, this chapter will examine evidence for the trophic or functional mechanisms underlying each of these relationships, while simultaneously summarising available information on the adaptive capacity of seabirds to respond to variability in these phenomena. Combined, the various components of this chapter will allow the overall vulnerability of seabirds on the GBR to be assessed under current climate change scenarios.

This chapter also aims to increase general awareness and understanding of both the vulnerability of seabirds to climate change and the potential broader effects these same threatening processes have on trophic dynamics in tropical marine ecosystems. This increased understanding can then be used to guide informed management decisions that protect Australia's marine biodiversity while allowing for long–term sustainable use of the GBR ecosystem.

## 14.2 Seabirds on the Great Barrier Reef

For tropical seabirds in Australia, research to date has been centred in the Houtman-Abrolhos Island group of Western Australia, or on the GBR and in adjacent Coral Sea locations. The Houtman-Abrolhos colonies support over one million pairs of tropical seabirds and are the largest seabird breeding rookery in the eastern Indian Ocean[111]. Australia's Coral Sea Island territories also contain regionally significant populations of many of the 13 seabird species known to breed there. North East Herald Cay is the principle seabird rookery within this region[24] (Baker et al. unpublished data).

The importance of the GBR as seabird breeding and feeding habitat on a national scale has previously been summarised in Hulsman et al.[57]. Seabirds breeding on the GBR constitute about 2.4 percent of the total population that breed in Australian continental waters. The enormous numbers of short-tailed shearwaters (*Puffinus tenuirostris*) that breed in southern Australia are included in this figure. This masks the true significance of the GBR as seabird breeding habitat. If short-tailed shearwaters are not considered, the GBR contains over 10 percent of Australia's breeding seabirds, ranking fifth in Australia in terms of the number of breeding pairs. The importance of the GBR increases when type and range of breeding species are considered. More than 25 percent of Australia's tropical seabirds nest on the GBR, including greater than 50 percent of Australia's roseate terns (*Sterna dougallii*), lesser-crested terns (*Sterna bengalensis*), black-naped terns (*Sterna sumatrana*), and black noddies (*Anous minutus*); and about 25 percent of the wedge-tailed shearwater (*Puffinus pacificus*), brown booby (*Sula leucogaster*), masked booby (*Sula dactylatra*) and red-tailed tropicbirds (*Phaeton rubricauda*)[57].

Most major seabird colonies are located in either the far northern, northern or southern regions of the GBR[57]. Raine Island in the far northern region is one of the largest and most significant tropical seabird breeding sites in Australia[66,117,67,86,113]. Of the 24 seabirds recorded as breeding in Queensland, 14 breed at Raine Island[8]. Recently Batianoff and Cornelius[8] have undertaken a comprehensive review of the trends in seabird numbers at this site since the beginning of last century.

Michaelmas Cay in the northern region of the GBR is a tropical seabird colony rated as the second most important nesting site in the GBR[46]. The island constitutes a major nesting site for sooty terns (*Sterna fuscata*), common noddies (*Anous stolidus*), crested (*Sterna bergii*) and lesser-crested terns (*S. bengalensis*)[65,68]. At Michealmas Cay demographic parameters for these four principal species have been collected from 1984 to 2001 as part of the coastal bird atlas (Queensland Parks and Wildlife Service). These data are of critical importance as they represent one of the few large long-term seabird monitoring data sets in Australia[22], and one of the few focused on a tropical region globally (Table 14.1a,b).

***Table 14.1a*** *Local scale studies that correlate environmental variability with effects on various reproductive parameters, and proposed mechanisms*

| Paper | Location | Temperate/ Tropical | Species | Environmental Parameter | Seabird Parameter | Proposed mechanism? | Long/ Short term |
|---|---|---|---|---|---|---|---|
| Heatwole et al.[53] | Local | Sub-tropical | brown booby, silver gull | Reductions in available food, probably associated with ENSO-associated SST increases; deterioration of nesting habitat possibly related to frequency of severe storms | Population size | Reductions in available food, probably associated with ENSO-associated SST increases | Inter-annual |
| Smithers et al.[106] | Local | Sub-tropical | wedge-tailed shearwater | SST | Chick growth and foraging success | Changes in SSTs entrained by large-scale processes such as ENSO cause seasonal-scale declines in productivity at lower trophic levels | Inter-annual |
| Peck et al.[92] | Local | Sub-tropical | wedge-tailed shearwater | SST | Chick growth and foraging success | Associated underwater predators or forage fish either leave area or move to cooler deeper water | Within-season |
| Dyer et al.[36] | Local | Sub-tropical | wedge-tailed shearwater, black noddy | None | Population size |  | Inter-annual |
| Erwin and Congdon[38] | Local | Sub-tropical | black noddy | SST | Chick growth and foraging success | Associated underwater predators or forage fish either leave area or move to cooler deeper water | Within-season |
| Blaber et al.[12] | Local | Tropical | great frigatebird, least frigatebird, brown booby, roseate tern, black-naped tern, sooty tern, bridled tern, common noddy, black noddy, crested tern, lesser crested tern, caspian tern | Effects of trawling | Population size | Extra food in the form of trawl discards may influence breeding success and hence population size in some species | Inter-annual |

| Paper | Location | Temperate/ Tropical | Species | Environmental Parameter | Seabird Parameter | Proposed mechanism? | Long/ Short term |
|---|---|---|---|---|---|---|---|
| Baker et al. unpublished data | Local | Tropical | red-footed booby, great frigatebird, least frigatebird, red-tailed tropicbird, black noddy, masked booby, wedge-tailed shearwater | ENSO-associated increases in SST | Population size |  | Inter-annual |
| Batianoff and Cornelius[8] | Local | Tropical | wedge-tailed shearwater, masked booby, red-tailed tropicbird, brown booby, least frigatebird, red-footed booby, bridled tern, sooty tern, common noddy | Lack of correlation with significant increases in human disturbance or habitat loss and/or deterioration of nesting habitat suggests decreases in food availability probably related to ENSO-associated increases in SST | Population size | Population decline in 13 of 16 spp over 24 year period (69.7% reduction of total population of rookery); no evidence of significant human disturbance, no habitat loss/deterioration of nesting habitat | Decadal |
| Erwin and Condon[37] | Local | Tropical | sooty tern | SST and daily fisheries catch | Foraging success | Associated underwater predators and/or forage fish either leave area or move to cooler deeper water | Within-season |
| Erwin and Congdon[39] | Local | Tropical | sooty tern, common noddy | SST and daily fisheries catch | Size of the breeding population | Precursors to traditional parameters associated with ENSO events-depth of the thermocline | Within-season |

**Table 14.1b** *Principal regional-scale studies that correlate environmental variability with affects on various reproductive parameters, and proposed mechanisms*

| Paper | Location | Temperate/ Tropical | Species | Environmental Parameter | Seabird Parameter | Proposed mechanism? |
|---|---|---|---|---|---|---|
| Lyver et al.[76] | Regional: New Zealand | Temperate | sooty shearwater | SOI and SST anomalies in the following 12 months | Harvest rates and burrow occupancies | Significant precursors in SST around Pacific up to 1 year prior to ENSO |
| Bunce et al[17] | Regional: Victoria | Temperate | Australasian gannet | Mean monthly SOI and mean monthly SST; changes in activities of commercial fisheries | Population trends (3 fold increase since 1980s) | Short supply of food as result of severe curtailment of upwelling |
| Chambers[21] | Regional: Victoria | Temperate | little penguin | Local scale SST, global scale SST and SOI | Breeding success, date of egg laying, hatching success, number of chicks raised per pair and weight of chicks when left nest | During ENSO events increases in westerly winds over Tasmania result in upwelling of nutrient-rich cold subantartic waters which has been associated with increases in a number of commercially important fish stocks |
| Dunlop et al.[33] | Regional: Western Australia | Sub-tropical | wedge-tailed shearwater | Three year aggregate annual SOI | Three year running mean in active burrow numbers | ENSO robust controller of marine variables such as SST, salinity and sea level and hence associated with recruitment rates of various prey |
| Nicholson[84] | Regional: Western Australia | Sub-tropical | wedge-tailed shearwater, bridled tern, crested tern, lesser crested tern | Monthly SOI, SST and cyclonic activity | Breeding success, meal size and feeding frequency, chick growth | Differences in ocean temperatures across years associated with ENSO influencing fish populations and activity |
| Surman et al.[111] | Regional: Western Australia | Sub-tropical | wedge-tailed shearwater, sooty tern, roseate tern, common noddy, lesser noddy, crested tern | ENSO patterns and fisheries activity | Diets and breeding patterns- hatching success, fledging success and breeding success | Change in distribution of prey associated with ENSO-driven ocean temperature changes |

| Paper | Location | Temperate/ Tropical | Species | Environmental Parameter | Seabird Parameter | Proposed mechanism? |
|---|---|---|---|---|---|---|
| Schreiber and Schreiber[104] | Global | Tropical | red-footed booby, masked booby, brown booby, red-footed booby, great frigatebird, least frigatebird, red-tailed tropicbird, sooty tern, grey-backed tern, common noddy, white tern, crested tern | ENSO event | Breeding participation/success | Depression of prey availability from unusual ocean currents and thermocline as a response to atmospheric forcing of ENSO |
| Schreiber[102] | Global | Tropical | red-tailed tropicbird | ENSO event | Provisioning and chick growth | Nutrient content of water decreases and fish die or leave area due to ENSO |
| Cruz and Cruz[29] | Global | Tropical | dark-rumped petrel | Marine primary productivity | Chick growth rate and timing of fledging | Short supply of food as result of severe curtailment of upwelling |
| Boersma[13] | Global | Tropical | Galapagos penguin | Three month average SOI | Reproduction, body condition, population trends and distribution | Overall warming in Pacific during last 20 years associated with more frequent El Niño events and less frequent La Niña events; reduced advection and upwelling during ENSO |
| Ramos et al.[95] | Global | Tropical | roseate tern | MEI over laying season; average SST for month of breeding inititation | Timing of breeding; size of breeding population | Influence of factors such as predatory fish on food availability overridden by importance of weather events and oceanographic conditions which determine marine productivity |
| Ramos et al.[96] | Global | Tropical | white-tailed tropicbird | Average monthly MEI | Reproductive success | Changes in food availability caused by changes in oceanographic-atmospheric parameters where periods with higher MEI are linked with lower ocean productivity |
| Ramos et al.[97] | Global | Tropical | common noddy | Occurrence El Niño or La Niña | Timing of breeding, productivity, growth rates and adult body condition | ENSO linked to high SST and lower ocean productivity |

* MEI = multivariate El Niño Index; SOI = Southern Oscillation Index

The islands of the Swain reefs in the far southeast of the GBR constitute one of six core seabird breeding areas[67,53]. Bi-annual census of seabird populations in the Swains reefs have been collected over more than a ten year period from 1984 to 1995[53].

Finally, the Capricorn-Bunker group of islands in the southern GBR also contains nationally and internationally significant seabird breeding populations. This island group supports the Pacific Ocean's largest breeding colony of wedge-tailed shearwaters[36]. The Capricornia Cays also contain 73 to 75 percent of the seabird biomass of the GBR[110], and over 97 percent of the black noddy populations of the GBR[36]. There have been approximately 15 censuses of black noddies breeding at Heron Island between 1910 and 2000, including a series of annual comprehensive surveys of the population in the whole Capricorn-Bunker group from 1996 to 2000[57,36].

Many seabird species that breed within the GBR and in adjacent areas are considered migratory species and/or threatened species and are listed under the *Australian Environmental Protection and Biodiversity Conservation Act 1999*[a] in a variety of categories. Many are also variously protected under international agreements such as the China-Australia Migratory Bird Agreement (CAMBA), Japan-Australia Migratory Bird Agreement (JAMBA) and the Convention on the Conservation of Migratory Species of Wild Animals (Bonn Convention 1979). Additionally, the GBR region hosts migrating populations of some northern hemisphere breeding species such as common tern (*Sterna hirundo*) and much of the Asian population of roseate tern[88].

## 14.3 Vulnerability of seabirds to climate variation

Most previous studies (Table 14.1b) document the impact of climate on seabirds as seasonal or longer-term correlations between reproductive demographics and large-scale oceanographic processes, such as the El Niño-Southern Oscillation (ENSO). Specifically, this work suggests that ENSO type phenomena impact important demographic parameters, such as the timing of breeding, year-to-year recruitment, number of breeding pairs and hatching success on an annual or longer-term basis[116,49,94,95,62]. Both beneficial and detrimental seasonal or longer-term impacts have been observed in a number of temperate ecosystems[69,54,34,47], but to date only detrimental effects have been documented in tropical ecosystems.

As well as these larger-scale longer-term impacts, there is also recent evidence that sea temperature variation at smaller within-season and day-to-day time scales significantly impacts seabird foraging success, growth patterns and reproductive output, regardless of prevailing ENSO type conditions. While not totally independent these longer- and shorter-term processes may operate on different reproductive parameters and involved substantially different trophic interactions. Therefore, documented impacts at each of these scales will be examined separately, along with available evidence of the possible trophic mechanisms responsible for each.

Other climate driven processes that may influence seabird distribution and abundance include sea level rise, changing rainfall patterns and changes to the frequency and intensity of tropical storms and cyclones. However, for these processes significantly fewer data are available from which to establish current impacts. Therefore, this group of phenomena can only be considered in less detail.

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[a] For more information see: http://www.environment.gov.au/cgi-bin/sprat/public/publicthreatenedlist.pl?wanted=fauna

Finally, predicted changes to ocean chemistry and light/ultraviolet (UV) radiation (Lough chapter 2) will impact seabirds via trophic interactions that destabilise overall reef trophic ecology and reduce food resource availability. The potential impacts of these phenomena at lower trophic levels and the possibility that these impacts may cause trophic collapse are discussed in earlier chapters in this volume. The predicted changes in ocean chemistry and UV are not considered significant for seabirds and until further information becomes available, the likely effect of changing ocean chemistry and light/UV radiation on seabirds remains extremely difficult to predict. For this reason these phenomena will not be considered further in this chapter.

## 14.3.1 Seasonal-scale and longer-term climate variability

### *14.3.1.1 Seasonal-scale and longer-term impacts*

A number of natural circulation patterns, most importantly the North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO) and the El Niño-Southern Oscillation (ENSO), drive global climate variation[61]. The influence of these processes on seabirds varies with geographic location and each tends to operate at different temporal scales. The ENSO produces the strongest natural climatic fluctuations at inter-annual time-scales. The NAO displays irregular oscillations on inter-annual to multi-decadal time-scales, while the PDO is associated with decadal to multi-decadal climate variability. Within each ocean basin, extreme variations in seabird reproductive performance have been related to both seasonal-scale[33,95,103,106] and longer-term[104,2,102] fluctuations in these major oceanographic phenomena.

*North Atlantic Oscillation (NAO)* – In the Atlantic Ocean, large-scale fluctuations in the NAO have been observed to impact a wide range of seabird demographic parameters[35]. For example, annual variability in the breeding performance of northern fulmar (*Fulmarus glacialis*) has been linked to variation in both the winter NAO and Northern Hemisphere summer temperatures with a time lag of up to five years[114]. Reduced adult survival and altered breeding phenology in North Atlantic alcid and kittiwake species has also been closely correlated with lagged effects from the NAO and associated sea temperature increases[42,101].

The NAO and changes in Arctic sea ice are thought to be closely coupled[61] and the limited number of studies from the Arctic Ocean show changes in seabird breeding phenology, reproductive output and adult body mass related to sea ice changes[1]. Breeding phenology of thick-billed murre (*Uria lomvia*) at Arctic colonies in both the northern and southern limits of the species range is positively correlated with summer ice cover. Documented trends suggest that increased global temperatures during winter and spring benefit populations at the northern limit of this range but adversely affect populations on the species southern limit[45]. The recent positive temporal trend of the NAO has also been correlated to changes to both natal and breeding dispersal in Arctic terns (Sterna paradisaea)[82]. Southern Ocean examples of similar relationships include decadal scale population changes in adélie and emperor penguins (*Pygoscelis adeliae* and *Aptenodytes forsteri*) that have been closely related to winter sea ice extent[28].

*Pacific Decadal Oscillation (PDO)* – In the eastern Pacific the ongoing 30-year warm phase of the PDO[41] has been associated with significant breeding population declines of Cassin's auklets (*Ptychoramphus aleuticus*), and with the northward retraction of multiple Pacific Ocean subarctic species including albatrosses, shearwaters and murres[1]. In the same region numbers of migrating sooty shearwaters

(*Puffinus griseus*), the most abundant species in the California current system, have declined 90 percent since the 1980s[116]. This decline is thought to be linked to decreasing zooplankton volume associated with reduced upwelling and increasing sea-surface temperatures over the same period[1].

*El Niño-Southern Oscillation (ENSO)* – Tropical waters comprise half the total open water on earth[74] and ENSO-associated variability and fluctuations in sea surface temperature are greatest in the tropics[41]. Increasingly, data correlating reproductive parameters with global climate phenomena for tropical seabirds (Table 14.1b) demonstrate the potential for ENSO-associated variability to have severe detrimental impacts in tropical ecosystems at a range of different temporal scales. Substantial data exist for the central and southeast Pacific where detailed results correlate ENSO frequency and/or intensity with lengthened fledging periods, slowed chick development, a reduced incidence of breeding, and significant decreases in nesting success[2,13].

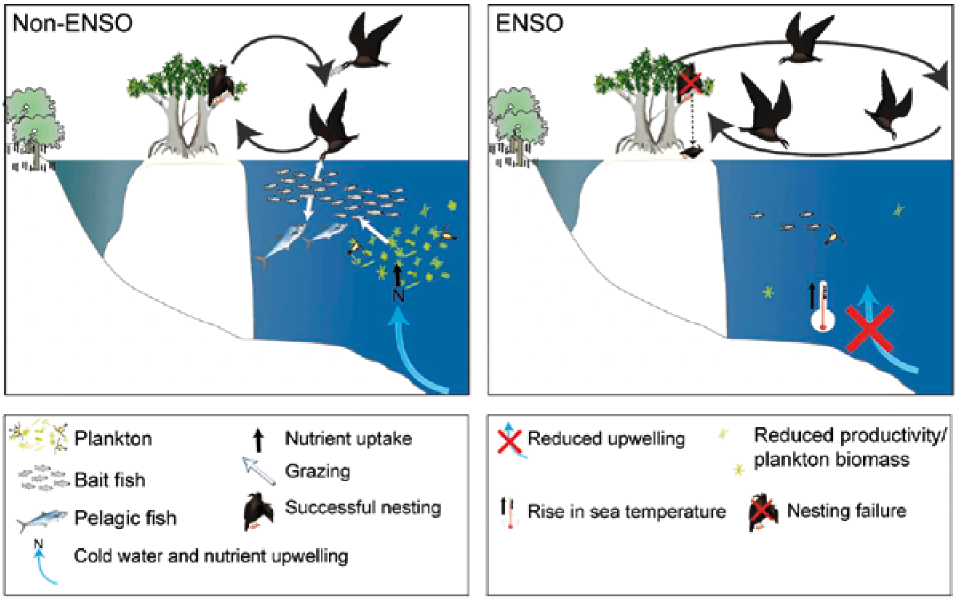
A single severe ENSO event in 1982 to 1983 produced both reproductive failure and high adult mortality in multiple seabird species breeding at Christmas Island in the central Pacific[104,2,102]. These populations took more than a decade to regain their pre-ENSO levels[103], with brown boobies (*Sula leucogaster*) being one of the slowest species to recover[104]. Christmas bird count data for another location in the central Pacific following this same ENSO event showed population declines of between 65 and 96 percent for red-footed boobies (*Sula sula*) and great frigatebirds (*Fregata minor*), respectively[115]. Similar population crashes were also recorded for cormorant and murre populations in the eastern Pacific Ocean in association with El Niño intensity[115].

In the Indian Ocean seabird reproductive biology has been strongly tied to ENSO-driven processes. For example, in the Seychelles seasonal-scale variation in ENSO intensity and sea temperature have been correlated with changes in both food availability and timing of breeding for two noddy species (black noddy and common noddy) and roseate terns[97]. Common noddies bred later, less successfully and with significantly reduced body condition[97]. For roseate terns, larger-scale ENSO-associated fluctuations also affect the timing of breeding, while local variation in sea temperature impacts the size of breeding populations[95].

Within tropical, subtropical and temperate Australasia, significant impacts on seabird biology have been linked primarily to fluctuations in the ENSO. In Western Australian colonies, sensitivity to oceanographic conditions during ENSO years has resulted in delayed breeding and poor breeding success in wedge-tailed shearwaters and poor foraging returns for at least three of four tropical tern species (Table 14.1). At these colonies the number of active wedge-tailed shearwater burrows excavated per season directly reflected fluctuations in ENSO and oceanographic conditions from previous years: there being a significant correlation between the three-year running mean in active burrow numbers and the annual Southern Oscillation Index over the same period[33]. In temperate eastern Australasia during the 2002 ENSO event, sooty terns at Lord Howe Island experienced almost complete breeding failure, with virtually all chicks that hatched dying of starvation (L. O'Neill pers comm). This reproductive crash followed a non-ENSO year with approximately 99 percent fledging success.

Large-scale ENSO processes have also been associated with negative impacts on tropical seabird breeding success in the Coral Sea and along the northeast Australian coastline, especially for colonies on or adjacent to the GBR (Figure 14.1). Such impacts have been particularly obvious during events like the 1997 and 1998 ENSO. Extremely high sea surface temperature increases during this event were also accompanied by severe reef-wide coral bleaching[55,10].

***Figure 14.1*** *Breeding success of seabirds has been impacted by environmental changes associated with ENSO events; for example, reduced primary productivity of plankton can lead to reductions in food availability for hatchlings*

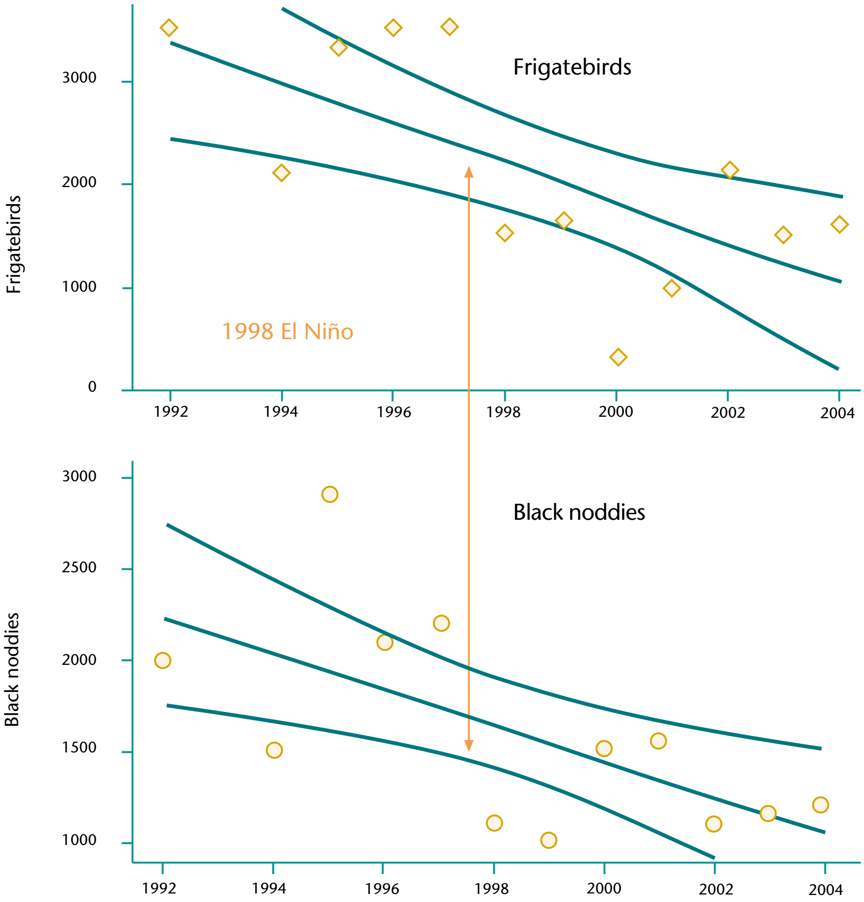


For Coral Sea populations, data over the 12-year period from 1992 to 2004 show significant declines equivalent to greater than 6 to 7 percent per annum for populations of great and least frigatebirds (*Fregata minor, F. ariel*) and possibly black noddies at this site[50] (Figure 14.2; Baker et al. unpublished data). Significant change in numbers of these species appears to relate to population crashes at the time of the 1997 to 1998 El Niño event. Numbers of each species remained relatively stable both before and after this event. Importantly, despite a return to presumably more favourable conditions, both the frigatebird and noddy populations have still not returned to their pre-1998 levels.

Breeding populations of both red-footed boobies and red-tailed tropicbirds in the Coral Sea have also fluctuated substantially over the 1992 to 2004 period, but based on increased numbers of sightings during annual counts in 2003 to 2004, these species appear not to have declined below pre-1998 levels. Adult breeding populations of masked boobies and wedge-tailed shearwaters have changed little during this 12-year period and no decreases were observed in association with the 1997 to 1998 ENSO event, although fewer data are available to test trends for these species.

Current population data at Raine Island in the far northern GBR indicate a potential progressive decline in breeding populations of at least 10 of the 14 breeding species. This negative trend is consistent across all species with relatively large breeding populations. Declining species listed in descending order of reduction are: common noddy (95.5%), sooty tern (84.4%), bridled tern (*Sterna anaethetus*) (69.1%), red-footed booby (67.9%), least frigatebird (67.6%), brown booby (40.4%), red-tailed tropicbird (38.5%), masked booby (26.9%) and wedge-tailed shearwater (18.6%)[8].

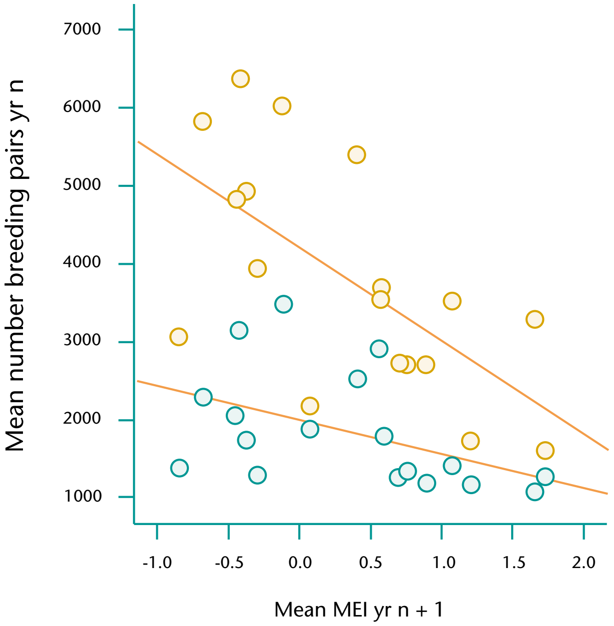
***Figure 14.2*** *Declines in frigatebird and black noddy populations at Northeast Herald Cay in the Coral Sea Marine Protected Area between 1992 and 2004 (Baker et al. unpublished data)*



The cause of the apparent declines at Raine Island is unknown. However, there is no evidence of significant human disturbance, and no deterioration of nesting habitat or habitat loss over the period of decline[8]. This lack of other mechanisms, and the fact that species which commonly form foraging associations at-sea have similar declining trends, highlights depletion of marine food stocks linked to changing climate and oceanographic regimes and/or human influences such as trawling as the most likely possible driving factors[8].

Eighteen years of data from Michaelmas Cay in the northern GBR also show significant relationships between population trends and ENSO climatic indices at multiple levels[39] (Erwin et al. unpublished data). Of primary importance is that breeding populations of the two pelagic foraging species, the sooty tern and common noddy, showed significant negative correlations with ENSO intensity in the year following each breeding survey (Figure 14.3). Similar relationships were not found for the inshore foraging crested tern that is thought to supplement natural food sources with discards from trawlers[12].

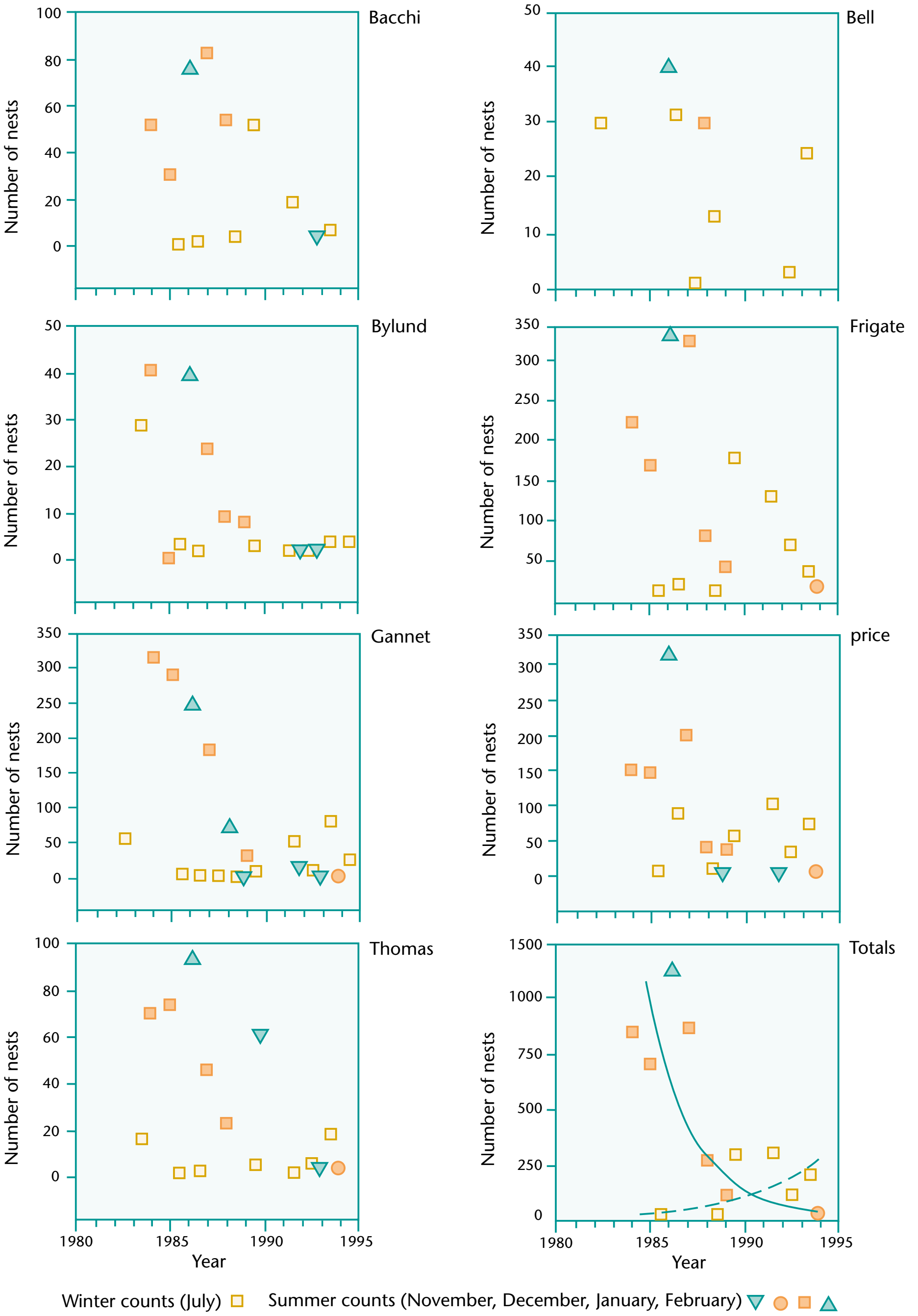
***Figure 14.3*** *Significant negative relationships between mean annual multivariate El Niño Index (MEI) in year n + 1 and mean annual numbers of breeding pairs of sooty terns (○) and common noddies (○) breeding at Michaelmas Cay in year n*[39]



These findings imply that the number of pelagic foraging adult terns that return to Michaelmas Cay to breed in any given year can be significantly impacted by ENSO precursors long before ENSO indices register an impending event. Significant negative relationships between precursor changes in the depth of the 20°C thermocline and the number of breeding pairs of sooty terns and common noddies at Michaelmas Cay[39] suggest a plausible mechanism for the observed 'predictive' ability of these pelagic tropical terns. Similar relationships between breeding numbers and the direction and intensity of ENSO and sea temperature anomalies over the following 12 months have also been observed in sooty shearwaters breeding in New Zealand[76] and multiple seabird species breeding along the southern African coast[70]. Further analyses of sooty tern and common noddy data for Michaelmas Cay also suggest that levels of recruitment are impacted over longer periods, negative impacts being clearly manifested as poor recruitment to the breeding population approximately three years after ENSO conditions (Erwin et al. unpublished data).

Long-term data on seabird abundance and demography from the Swains Reefs in the southern region of the GBR show negative population trends for brown boobies in both the number of active nests and total adults on all but one of seven islands studied. Figure 14.4 illustrates the cumulative declines that occurred on individual cays as well as the overall tends. This figure clearly shows that the declining trend was consistent throughout the region and was not simply a consequence of inter-seasonal migration between islands[53]. The causes of these significant declines are unclear, but the authors believe that they are unlikely to be human disturbance induced. Aerial surveillance data obtained over the same period suggest no increase in the level of human visitation to the area[53].

***Figure 14.4*** *Number of brown booby nests recorded between 1980 and 1995 on seven cays in the Swains Reefs (source Heatwole et al.*[53]*)*



Similarly, there are no data to suggest that changes in charter or fishing boat operations have caused higher levels of seabird disturbance. Instead, the most likely explanation for the declines is purported to be decreases in food availability associated with three significant ENSO events that occurred between 1984 and 1995[53]. The presence of high numbers of emaciated brown booby chicks following these events further suggests that food availability linked to ENSO variation played a major role in the observed declines[53]. Masked booby did not exhibit similar declines, possibly because of differences in its feeding ecology[53], although the exact reasons for species-specific differences in response are unknown. More recent data for Gannet Cay within the Swains group indicates the impacts of the larger 1997 to 1998 and 2002 events are barely discernible because breeding numbers have not recovered from declines that occurred during the 1980s (Figure 14.5).

Wedge-tailed shearwaters and black noddies numerically dominate breeding seabird species of the Capricorn Island group in the southern GBR[67,58,36]. The black noddy population on Heron Island has increased exponentially since early last century[7,85], however, recent censuses on Heron Island demonstrated a substantial decrease in active nests from approximately 70,000 to 30,000 between 1996 and 2000[36]. Mass mortality of both adults and chicks was observed in January 1998 coinciding with the 1998 ENSO event and extensive coral bleaching in the region[9].

Similarly, in 2002, a second year of abnormally high sea surface temperature, reduced provisioning, decreased growth rates and almost complete reproductive failure of wedge-tailed shearwaters occurred at Heron Island[106]. Compared with data from the previous year, adult shearwaters were unable to compensate for changes in either the availability or accessibility of forage-fish by increasing food loads or foraging rates.

***Figure 14.5*** *Decline in numbers of active brown booby nests (summer) at Gannet Cay in the Swain Reefs GBR during the period 1976 to 2004 (Heatwole et al.[53], O'Neill et al. unpublished data)*

### *14.3.1.2 Seasonal-scale and longer-term trophic mechanisms*

In general, the observed large-scale upper trophic level impacts of climate variability described above have been attributed to interrelated seasonal-scale decreases in productivity or prey species abundance at lower trophic levels[108,34,60]. These studies propose that, during intense ENSO events, unfavourable sea temperatures disrupt or block nutrient rich upwelling zones, thereby disrupting phytoplankton distribution and abundance[77,64,122]. This in turn produces seasonal-scale declines in productivity at lower trophic levels[100,108] that impact recruitment of seabird prey species[104,30,108,109,34].

Work in temperate ecosystems has expanded this model by showing that sea surface temperature variation can induce changes in the timing of peak productivity during spawning or juvenile life-history stages of prey species. Such changes can impact seabird breeding success via phenological 'mismatches' between prey recruitment and seabird breeding requirements[11,54,34,42]. By definition, these models predict that foraging success during ENSO events should be lower at the beginning, and possibly for the duration of the breeding season, and that these impacts will be general across all seabird species using the impacted resources.

A third seasonal-scale hypotheses is that particular food types may be associated with individual water masses that move out of reach of breeding birds during ENSO events[59,69]. This hypothesis has even greater merit if the vertical, as well as horizontal distribution of potentially favourable water masses is considered. For example, the reason that pelagic foraging sooty tern and common noddy are sensitive to ENSO precursors up to twelve months in advance of an ENSO event is closely associated with changes in the depth/gradient of the Pacific Ocean thermocline[39]. Many seabird taxa are known to forage in association with specific thermocline depths. In particular, eastern tropical Pacific piscivorous seabirds have been shown to forage preferentially in areas where the thermocline is deepest and most stratified[107]. This suggests that any change in thermocline depth will significantly influence prey accessibility to these taxa. In the Pacific, substantial changes in thermocline depth and stratification are important precursors that can occur up to one year preceding ENSO anomalies[81,99].

While evidence exists in support of each of these seasonal-scale productivity or distributional models, most studies to date have not attempted to identify any direct mechanism linking ENSO and sea surface temperature variation with adult or fledgling survival. Therefore, the exact trophic mechanisms involved remain relatively unclear[32,77,51,109].

### *14.3.1.3 Seasonal-scale and longer-term vulnerability and thresholds*

In general, the accumulated evidence of impacts presented in the preceding sections clearly highlights the sensitivity of seabirds to variation in large-scale oceanographic phenomena. Unfortunately, there is little consistency in research methodology among these studies. Detailed comparisons between data sets are hampered by the wide variety of demographic, phenological and environmental parameters measured at different temporal and spatial scales. This makes it difficult to formulate and parameterise general models of impacts for specific climate change scenarios across different ecosystems or species. However, some generalities are apparent.

Significant impacts have been observed in all ocean basins as well as in all regions of the GBR and adjacent areas of Australasia. Impacts occur at inter-annual, decadal and even longer time scales and across taxonomic and functional groups. Virtually all taxa examined show some degree of impact at one or more locations, with these taxa being from different families, genera, and/or species.

Impacts have been observed to occur across all foraging guilds (ie inshore, offshore and pelagic species) with offshore and pelagic species appearing to be significantly more sensitive than inshore foragers. Negative impacts have also been observed on nearly all components of seabird reproductive biology, such as timing of breeding, year-to-year recruitment, number of breeding pairs, annual hatching and fledging success, chick growth and adult survival, etc. Combined, these finding imply that recent climate fluctuations linked to these large-scale oceanographic phenomena are already having significant detrimental impacts on seabird populations both globally and within the Australasian region. Available evidence also suggests that predicted changes in the frequency and intensity of phenomena associated with climate change trends are likely to further compound these impacts.

#### *14.3.1.4 Seasonal-scale and longer-term adaptive capacity*

As evidence of the influence of climate variation on seabird reproductive dynamics increases, it is becoming obvious that individual species and even individual birds with distinct phenotypic characteristics respond differently to climatic anomalies. Different responses are manifested depending upon diet[69,94,60], dispersal characteristics[42], sex[48,63], age[114,94,18] and the demographic parameters being measured[63]. Major differences in foraging ecology between species are presumed to be one of the main reasons for variable responses to ENSO conditions[39].

Different seabird species also show different sensitivity and rates of recovery to both ENSO events[104,96] and associated sea surface temperature anomalies dependant upon breeding location[69,60]. In the clearest example, varying rates of recovery over a two-year period were documented in seabirds nesting on Christmas Island in the central Pacific during the severe 1982 to 1983 ENSO event[104].

Why species-specific sensitivity differs between specific ENSO events and locations is unknown, but data suggest much of this variation may relate to interactions between a species' population size, foraging ecology, and the pattern and intensity of previous location-specific impacts. Such location and species-specific variations in response make generalising about adaptive capacity difficult and suggest that assessments of resilience or adaptive capacity will need to be undertaken on a colony by colony, or regional basis with data obtained specifically for that purpose.

### 14.3.2 Short-term and within-season climate variability

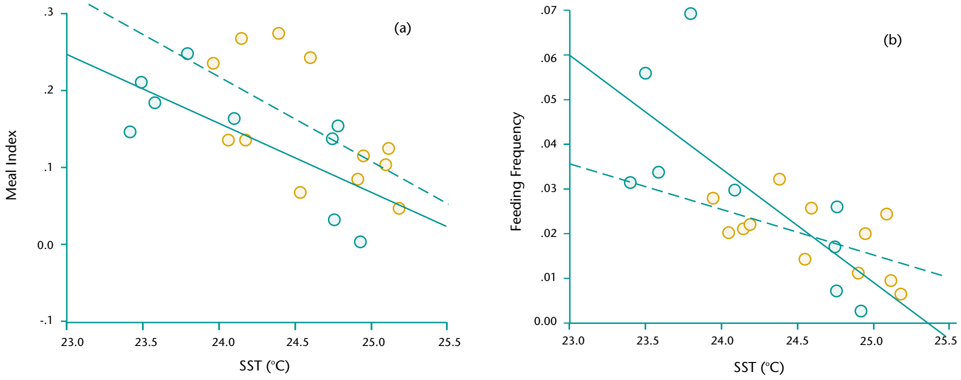
#### *14.3.2.1 Short-term and within-season impacts*

As discussed, most evidence of potential climate change impacts on seabirds comes from large seasonal-scale correlations between reproductive biology and ENSO type activity. The three seasonal-scale mechanistic hypotheses described above all involve within-season time lags between shifting sea surface temperature and the availability of prey species to seabirds[108,34]. Moreover, they predict that food availability should be lower and/or delayed over entire breeding seasons.

However, recent research in both the northern and southern regions of the GBR has highlighted previously undescribed spatial and temporal links between within-season variation in sea surface temperature and seabird reproductive success. Considerable evidence now exists that the foraging success of multiple seabird species fluctuates daily in direct association with small-scale variation in sea surface temperature. These relationships are consistent both within and among breeding seasons and have been observed in multiple study years regardless of prevailing El Niño conditions[92,37].

For example, at Michaelmas Cay during the latter two-thirds of two consecutive breeding seasons in 2004 and 2005, significant negative relationships were observed between day-to-day variation in sea surface temperature and both feeding frequency and the amount of food fed to sooty terns chicks (Figure 14.6). Both provisioning variables responded to changes in sea surface temperature in a similar manner among seasons. However, during 2004, both were consistently lower for equivalent sea surface temperature values, suggesting that food was generally less abundant[37]. Consistency in the rate at which food availability changed between years implies that short-term variation in sea surface temperature impacted sooty tern provisioning similarly across breeding seasons for temperature ranges of 23 to 26°C as measured at Michaelmas Cay. Neither season was significantly influenced by ENSO driven anomalies in sea surface temperature or ocean circulation.

***Figure 14.6*** *Sterna fuscata: effect of daily sea surface temperature (SST) at Michaelmas Cay on (a) age-adjusted Meal Index (○), 15 September to 3 October) of 2004 and (○), 20 May to 22 June) of 2005 and on (b) age-adjusted feeding frequency during the same periods in 2004 (○) and 2005 (○)*[37]



During the beginning of each breeding cycle in both 2004 and 2005, rapid changes in foraging success and food availability also occurred at Michaelmas Cay that were independent of, and an order of magnitude greater than, those attributable to day-to-day variation in sea surface temperature. This highlights that sea surface temperature variation in the vicinity of Michaelmas Cay may only impact foraging success during periods of low food availability and that other within-season mechanisms also have a significant influence on sooty tern reproductive potential. Limited evidence from the same data set suggests the distribution of subsurface predators as one possibility[37]. That other processes may also operate is significant, as the potential for these as yet unidentified trophic links to be impacted by climate change is unknown.

Day-to-day fluctuations in prey availability and reproductive success have also been correlated with small-scale day-to-day variation in sea surface temperature for wedge-tailed shearwaters and black noddies at Heron Island[92,38]. For wedge-tailed shearwaters daily increases in sea surface temperature negatively impacted average meal sizes, feed frequencies and chick growth rates, both within and among seasons[92] (Figure 14.7a-c). During 2003, a 1°C increase in sea surface temperature reduced

feeding frequency from approximately one night in two, to one night in five and daily chick mass gains were reduced by approximately six to seven percent of body weight per day.

Similarly, detailed studies of black noddy reproductive success during an extreme warm water event (1 to 1.5°C above long-term averages) in December 2005 to February 2006 showed significant negative relationships between day-to-day variation in sea surface temperature and adult provisioning rates, daily meal mass and relative chick growth[38] (Figure 14.8a-c). For each 1°C increase in sea surface temperature over the study period, feeding frequency declined on average by one-half a meal per day for each chick (from an average of approximately 3 meals per chick per day) and daily chick mass gains were reduced significantly. These findings were consistent with results for the northern GBR on the relationship between sooty tern foraging success and day-to-day variation in sea surface temperature[37].

In each of the three studies described above, significant decreases in prey availability tracked changes in sea surface temperature over short time scales and did not remain depressed over entire breeding seasons. These findings provide the first evidence that declines in seabird breeding success previously coupled exclusively to seasonal, yearly or decadal scale El Niño variation may not exclusively involve large-scale, inter-annual processes. Instead, these impacts may also result from the cumulative effects of day-to-day trophic interactions that operate within all breeding seasons.

***Figure 14.7*** *Puffinus pacificus: the relationship between: (a) sea surface temperature at Half-tide rocks (SSTHALF) and meal mass per gram of chick (MMASS); (b) SSTHALF and feeding frequency (FFREQ) during the 28 day study period in 2003; (c) change in chick mass per gram of chick (CMASS) and SSTHALF.during the 2003 study period*[92]

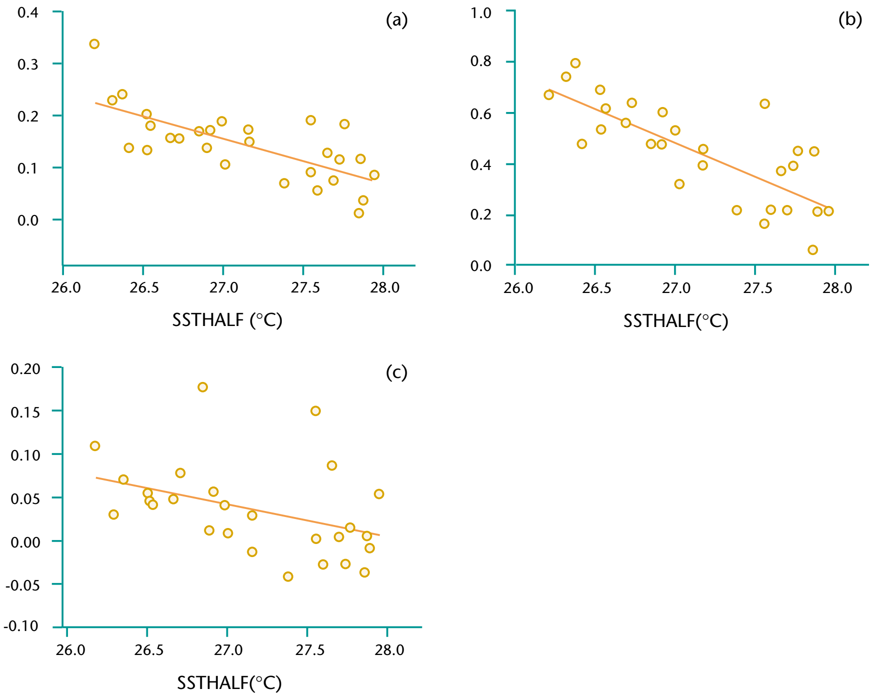
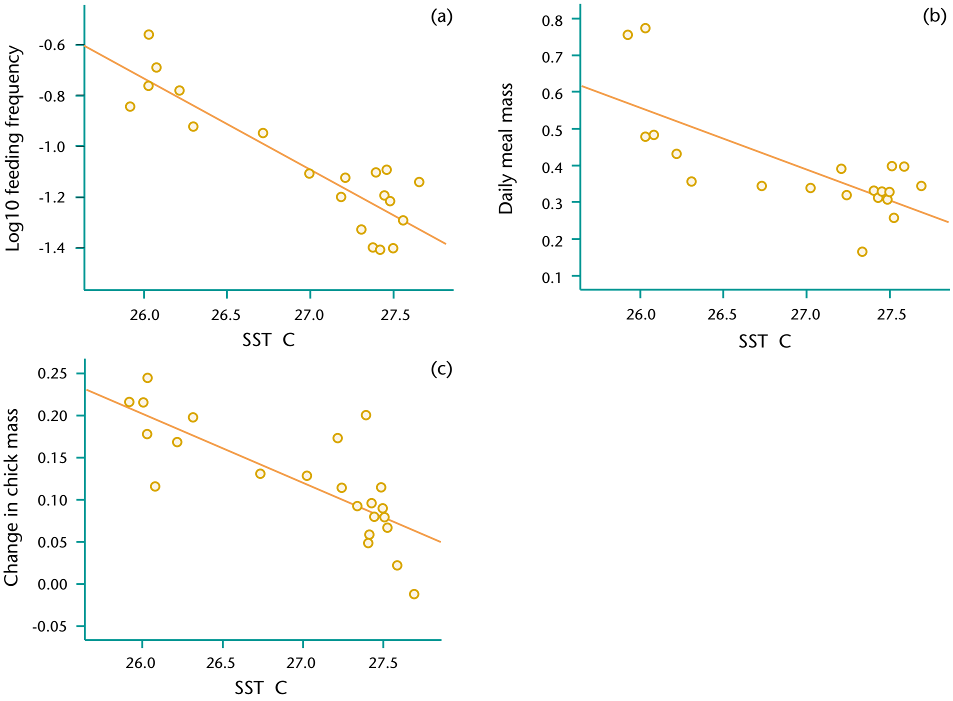


***Figure 14.8*** *Anous minutus: significant negative relationships between (a) sea surface temperature (SST) at Heron Island and log10 transformed feeding frequency during December 2005; (b) SST and meal mass per gram of chick and; (c) 24-hour chick mass change per gram of chick and daily SST[38]*



This is a mechanism that operates on much shorter temporal-scales than previously thought[29,116,49,95]. An assessment of data available for Southern Ocean species[89] also suggests that short-term variations in prey abundance are strongly associated with day-to-day fluctuations in sea surface temperatures, regardless of prevailing ENSO conditions, although these data have not been specifically analysed to test for such relationships.

### *14.3.2.2 Short-term and within-season trophic mechanisms*

Peck et al.[92] identify two trophic mechanisms previously described in the literature that may influence food availability to seabirds on a day-to-day basis. Firstly, fluctuations in sea surface temperature may affect the short-term vertical and/or horizontal distribution of prey. Such rapid shifts in prey distribution could be driven by numerous physiological[123,20,118], ecological[64,78,79] and behavioural[107] factors. For example, the generally low productivity of most tropical waters means that foraging seabird may be required to track shifting zones of prey availability located in small areas of enhanced primary productivity[121]. The number and spatial and temporal distribution of these favourable sites will be related to changing patterns of oceanography and may be significantly depleted by increases in sea surface temperature.

Previously this mechanism has been assumed to effect seabird breeding success only at seasonal scales[80,49,69,83,107,112]. However, if prey species prefer specific temperature regimes it is reasonable to assume that rapid movement in vertical or horizontal space to preferred temperatures could decrease their accessibility to aerial predators on a day-to-day basis.

A second possible day-to-day mechanism is that sea surface temperature directly influences the abundance of sub-surface predators[72,95]. These predators drive prey to the surface making them available to seabirds[16,105,5]. The most important predators associated with this behaviour in the tropical Pacific Ocean are tuna (*Thunnus spp.*)[4,52]. Extensive work has documented a close relationship between foraging seabirds and tuna[52,6], and it is generally accepted that specific oceanographic parameters linked to sea surface temperature, particularly thermocline depth[107], are important to the foraging ecology of both these groups[73,75,14]. However, the complex relationships among tuna and oceanographic variation remain poorly understood[4,52,73,75]. Consequently, the validity of this mechanism requires further investigation.

### *14.3.2.3 Short-term and within-season vulnerability and thresholds*

To date there have only been a small number of studies examining the effects of day-to-day variation in sea surface temperature, but already this body of work suggests these effects are important. Significant negative impacts have been observed across multiple species and throughout the entire GBR. At present there are no equivalent studies from other regions.

Data available for the GBR also indicate that there are sea surface temperature limits above which provisioning rates are so poor that sooty tern, black noddy, wedge-tailed shearwater and possibly other species' chicks show zero or negative growth. Currently the exact species-specific sea surface temperatures at which zero growth occurs are not known. This is because data on existing day-to-day temperature effects use average sea surface temperature indices generated from multiple stationary data loggers positioned throughout the regions of interest. Determining this relationship more precisely for each species and location requires sea surface temperature data obtained from foraging dive profiles of individual birds so that provisioning rates can be directly linked to oceanography at each foraging site. However, from existing data it is possible identify the magnitude of change in sea surface temperature that is important. Regression models show that the chicks of all species so far examined receive no food or begin to show zero growth at between 2 and 4°C increases in background sea surface temperature.

Of course, the period of time over which sea surface temperature remains high is also important for determining the overall level of impact. The length of time that chicks can cope with food stress will be species-specific and will depend on chick energy requirements, which vary with chick age[98]. Chicks of Procellariiform seabirds in general and wedge-tailed shearwaters in particular, have physiological adaptations that allow them to cope with relatively long periods of food deprivation[90]. Chicks of smaller pelagic tern species maintain significantly lower body reserves and consequently adults need to provision more frequently. This suggests that terns will be more sensitive to shorter periods of higher sea surface temperatures than shearwaters. It also implies that wedge-tailed shearwaters maybe useful indicators of the maximum period that chicks of tropical pelagic species are able to cope with sea surface temperature increases of between 2 and 4°C. Young shearwater chicks (3 to 4 weeks post-hatching) commonly survive six to seven days without food and even periods of 12 days with only a single meal, but mortality consistently occurs after 8 to 10 days of no provisioning (Congdon unpublished data). Older chicks (4 to 8 weeks post-hatching) show similar levels of sensitivity. Chicks are able to survive for up to 20 days when provided only with a single meal, but mortality regularly occurs after 8 to 10 days of no provisioning (Congdon unpublished data).

Combined, these findings suggest that in any single breeding season a 4°C rise in sea surface temperature maintained for periods of two weeks or longer will cause catastrophic reproductive failure of pelagic foraging species. The significance of similar sea surface temperature increases to more inshore and offshore foraging guilds is currently unknown. However, observed declines in less pelagic species such as brown boobies and frigatebirds at some locations suggest such impacts may be substantial and require further detailed examination.

Despite the current lack of data for non-pelagic species, it is likely that relatively small increases in average sea surface temperature or in the number and duration of large hot water incursions into the GBR will cause repeated and catastrophic reproductive failure of many seabird species.

#### *14.3.2.4 Short-term and within-season adaptive capacity*

In the short-term, the adaptive capacity of seabirds within the GBR rests on the ability of either adult foraging behaviour or chick growth patterns to respond to sea surface temperature-associated decreases in food availability.

When local food resources surrounding a breeding colony are unable to simultaneously support both chick development and adult self-maintenance, Procellariiform seabirds often adopt a unique dual foraging strategy[119,120]. Adults alternate multiple short foraging trips in resource-poor, near-colony waters with longer trips to highly productive areas 'at-distance' from breeding colonies. During near-colony trips, adults assimilate little food and sacrifice body condition to satisfy chick energy requirements.

Wedge-tailed shearwaters breeding at Heron Island use this dual foraging strategy[27]. Foraging adults repeatedly performed short-trip cycles of multiple one to four day trips, followed by a single long-trip of eight to ten days during which they build body reserves that are passed onto chicks by not self-provisioning adequately during the early stages of the next short-trip cycle[27].

The use of this foraging strategy in the southern GBR implies that only resource-poor waters are readily available adjacent to breeding colonies and that there is extremely limited potential for adult shearwaters to increase either food loads or provisioning rates if they are to compensate for sea surface temperature-associated decreases in food availability. The inability of black noddies to increase provisioning rates during a period of increased sea surface temperature during 2005 suggests they may be similarly constrained. No data are available to make comparable predictions for other species or locations.

Less is known about the adaptive capacity of chick developmental patterns. Manipulative experiments on black noddy chicks suggest that pelagic foraging terns have a hieratical pattern of nutrient allocation during growth, where body reserves needed for maintenance are preferentially maintained at the expense of feather development[25]. This implies that chicks of these species can compensate, to some degree, for reduced food availability or greater variation in delivery rates by lengthening

fledging periods, as long as starvation does not become pathological or predation pressure increase. Inshore foraging species do not appear to have similar levels of flexibility in the way incoming nutrients can be allocated to different components of growth[56].

In addition, data for shearwaters suggest that different adult foraging environments cause coordinated divergence in chick developmental characteristics[91]. Shearwater growth patterns differ significantly between temperate and tropical locations. Relative to more temperate locations, chicks at Heron Island in a resource-poor foraging environment preferentially store and maintain body mass at the expense of skeletal development[91]. It is currently not known if this is a plastic response to seasonal variation in food availability, or a colony-specific physiological adaptation to long-term average provisioning rates. Based on existing evidence the latter seems more likely[91]. If correct this implies shearwater growth responses to increasing sea surface temperature can only occur via natural selection over generations and will not be effective in mediating any negative impacts in the short-term. Unfortunately, more data are required to clearly establish the level of developmental flexibility and potential response in this species.

### 14.3.3 Physical disturbance – tropical storms and cyclones

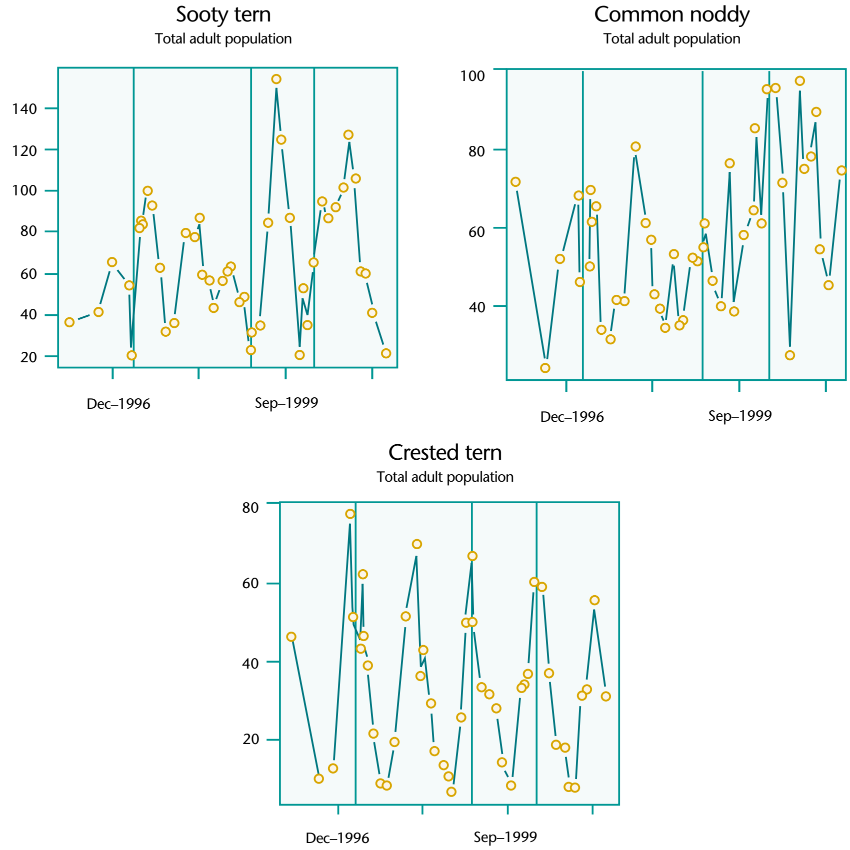
#### *14.3.3.1 Tropical storms and cyclones – impacts*

Climate change and associated ENSO variation have been predicted to increase the intensity and possibly the frequency of tropical storms and cyclones in the Australasian region (Lough chapter 2). Therefore, the exposure of seabirds to these phenomena can also be expected to increase accordingly.

Potential impacts on seabirds include the immediate effects of cyclones tracking over breeding sites, such as the destruction of eggs and increased mortality of chicks and adults, as well as the indirect impacts of wave inundation and erosion under the influence of gale force winds, storm tides and intensified currents[65]. Cyclones form over warm water. Therefore, there may also be a correlation between conditions under which cyclones form and lowered feeding success due to higher sea surface temperatures, as described in the previous section of this chapter. Delayed effects of cyclones may also be manifest through decreased recruitment associated with years of high chick loss, or years when cyclones reduce foraging success and so produce fledglings that are smaller than average and have lower survivorship[71,109]. At present populations of two relatively isolated and critically endangered species that breed on Christmas Island in the Indian Ocean, the Abbott's booby (*Papasula abbotti*) and the Christmas Island frigatebird (*Fregata andrewsi*), have been identified as vulnerable to increases in major storm or cyclone activity due to there restricted distributions and small population sizes[44, 23].

Only limited site-specific evidence of the potential impact of tropical storms on seabird reproductive biology is available (Table 14.1a,b). For the GBR region the majority of data come from the most intensely monitored population at Michaelmas Cay. Sooty terns at this site show individual instances of altered periodicity of breeding, declines in breeding numbers and reduced breeding success in association with cyclone activity[68]. This suggests that individual cyclones can significantly impact and limit the ability of Michaelmas Cay seabirds to reproduce in the short-term. However, longer-term trends do not demonstrate significant impacts of major tropical storms in the region. Both the incidence and intensity of cyclones are poor predictors of subsequent changes in the number of breeding pairs[31,40] (Figure 14.9).

***Figure 14.9*** *The total populations of sooty terns, common noddies and crested terns at Michaelmas Cay from 1996 to 2001. Cyclone occurrences are shown as green vertical lines; none showed an effect on populations for any of the three species (adapted from De'ath[31])*



Food availability at Michaelmas Cay is such that tropical pelagic terns are able to breed during most months of the year[68,40]. Therefore, cyclonic impacts at this site may be ameliorated should cyclone-affected breeders return to re-nest in subsequent months, or in the next cycle, with minimum overall impact to reproductive output. Such resilience to cyclone losses may not be possible at locations where food availability is more seasonal. At such sites the production from an entire year may lost after a severe cyclone.

### *14.3.3.2 Tropical storms and cyclones – vulnerability and thresholds*

A lack of other comprehensive data sets means that the longer-term effects of changes in cyclone frequency or intensity on seabird population stability remain largely unknown and unpredictable. However, the impacts of tropical storms and cyclones are specific to their level of overlap with sensitive breeding phases and the size of the breeding colony affected. Any increase in the frequency or intensity of these phenomena could be expected to increase both the spatial and temporal

potential for them to coincide with important reproductive periods and so cause significant negative impacts. Ultimately, increasing cyclone frequency and intensity is an additional stressor that, when combined with other ENSO and sea surface temperature related impacts previously described, is likely to further reduce foraging efficiency and suppress reproductive potential.

#### *14.3.3.3 Tropical storms and cyclones – adaptive capacity*

The potential for seabirds to adapt to, or compensate for, changes in the frequency and intensity of tropical storms is dependent on their ability to either adjust breeding phenology so as to better avoid peak periods of storm activity, or relocate to less impacted breeding sites. The capacity for seabirds breeding on the GBR to do either of these two things is largely unknown (also see section 14.4.3). Most suitable habitat appears to already support breeding populations. However, it is not known if these populations are at, or near, carrying capacity with regard to either food resource or breeding habitat availability.

### 14.3.4 Sea level rise and rainfall patterns

#### *14.3.4.1 Sea level rise and rainfall patterns – impacts*

Both rising sea level and altered rainfall patterns will influence seabird reproductive output through the effect they have on the availability of breeding habitat. Sea level rise will alter erosion and deposition patterns that effect island size, while changing rainfall regimes will cause significant changes in the distribution and abundance of specific vegetation types (Turner and Batianoff chapter 20). Based on this, sea level rise and changing rainfall patterns are likely to impact the majority of seabird breeding colonies within the GBR and Coral Sea region in some way. However, these are longer-term processes that are unlikely to have consistently negative impacts.

Changes in sea level and rainfall are also expected to alter flow regimes and discharge patterns for major coastal river systems adjacent to the GBR. Any potential impact of these changes on seabird reproductive biology will be via effects on primary productivity and trophic stability at lower trophic levels. The potential impacts of altered discharge regimes on trophic ecology within the GBR are discussed in chapter 19. Changes in sea level or variation in rainfall patterns have not previously been quantitatively linked to changes in the distribution and abundance of nesting seabirds.

#### *14.3.4.2 Sea level rise and rainfall patterns – vulnerability and thresholds*

Most seabirds have different species-specific breeding habitat requirements. Functional groups include: burrow nesters that need either a tree, hummock grass, or open beach rock over-story to stabilise soil structure and allow tunnelling (eg wedge-tailed shearwaters), tree nesters that require mature woodland and forest vegetation (eg black noddies), and open ground nesters that prefer ground vegetation ranging from bare sand or soil (eg brown boobies), through light grass cover (eg sooty tern, common noddy), to a dense grassy over story (eg bridled terns). Therefore, the long-term impacts of rising sea levels and changes to rainfall patterns will depend on exactly how these phenomena change the distribution and abundance of species-specific breeding habitat on the GBR (Turner and Batianoff chapter 20).

In general, breeding islands are unlikely to decrease in size in the short to medium term (Turner and Batianoff chapter 20) and so little detrimental impact is expected to result from a decrease in absolute breeding area within the GBR. Decreasing annual rainfall and potential increases in sand and rubble deposition rates at windward edges of islands are likely to favour colonising ground cover and woody shrub vegetation types. If so, tree and burrow nesting species that rely predominantly on mature Pisonia (*Pisonia grandis*) forest may be disproportionately negatively impacted by reductions in breeding habitat and so more vulnerable to these particular phenomena.

Ultimately the magnitude and significance of these impacts will be determined by whether breeding numbers at specific colonies are currently limited by habitat availability. For ground-nesting species at Michaelmas Cay there is no evidence to suggest that population numbers are currently habitat limited. For example, no significant relationships have been observed between the mean area of available nesting habitat each year and the mean number of breeding pairs of any species of seabird breeding at this cay[40].

Rising sea level or changes in vegetation patterns may also have specific negative impacts at some important breeding sites depending on the current distribution of available habitat. For example, at Raine Island in the far northern GBR rising sea level has the potential to flood the only cavernous beach rock areas available to burrow nesting seabirds such as red-tailed tropicbirds and to redistribute marine turtle nesting habitat such that levels of inter-specific disturbance of seabirds by turtles could increase by orders of magnitude.

#### *14.3.4.3 Sea level rise and rainfall patterns – adaptive capacity*

As with the ability to adapt to changes in tropical storm frequency, the potential for seabirds to adapt to, or compensate for, changes in the abundance and distribution of species-specific breeding habitat depends on their ability to relocate to suitable breeding sites elsewhere. As previously discussed, the potential for birds to move to alternative breeding locations is unknown within the GBR system.

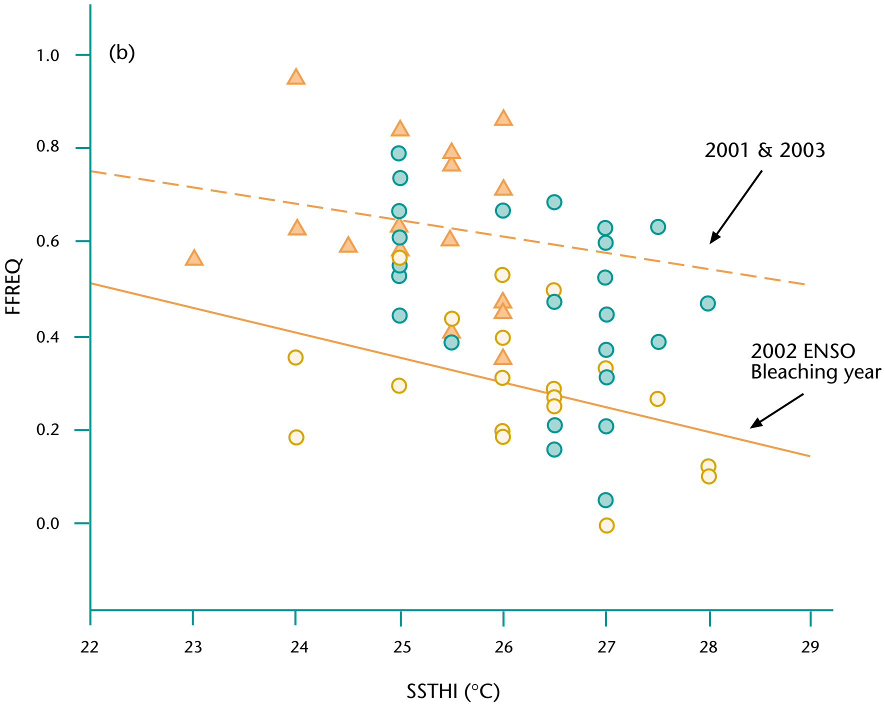
## 14.4 Linkages and interactions

### 14.4.1 Interactions between climate change stressors

Although data for the GBR suggest that the within-season impacts of sea surface temperature variation operate regardless of prevailing larger-scale ENSO conditions, these two processes are not mutually exclusive. Nor are their impacts independent of the influence of tropical storm and cyclone activity or other threatening processes.

For example, during an El Niño event in the southern GBR in 2002 seasonal-scale decreases in overall prey availability were observed as predicted by the large-scale models based on upwelling suppression, even after the daily effect of sea surface temperature variations were accounted for (Figure 14.10). During this ENSO event chick feeding frequencies were approximately one third those predicted to result from within-season sea surface temperature impacts alone[92]. This indicates that both inter-seasonal and within-season scale process were operating synergistically to depress foraging success and growth rates during this event. Consequently, the combined impact of both these phenomena

***Figure 14.10*** *Puffinus pacificus: the effect of sea surface temperature at Heron Island (SSTHI) on: feeding frequency ($F_{FREQ}$) in 2001 (▲), 2002 (○) and 2003(●).There was a significant effect of $SST_{HI}$ on $F_{FREQ}$ across years ($F_{FREQ} = 2.856 – 0.092\ SST_{HI}$). The effect of year on $F_{FREQ}$ was also significant. There was no effect of year on $SST_{HI}$. The dashed line represents the 2001–2003 regressions while the 2002 regression is represented by the solid line*[92]



on the long-term stability of seabird populations is likely to be considerably greater than the effects of each independently. Both processes need to be incorporated into any mechanistic models examining climate change related impacts on seabird breeding success at specific tropical locales.

Both inter-seasonal ENSO and within-season sea surface temperature impacts affect seabirds via the control they have on prey distribution and abundance. Therefore, there is potential for any other taxa that use similar prey to also be impacted. In particular, this could include many of the large predatory pelagic fish species known to forage in association with seabirds (Kingsford and Welch chapter 18).

### 14.4.2 Linkages between colonies and foraging resources

Wedge-tailed shearwaters from Heron Island use a dual foraging strategy. Adults forage locally in resource-poor waters to provision chicks, but also perform regular self-provisioning trips to specific sectors of ocean 'at-distance' from breeding colonies where localised oceanographic features such as seamounts or oceanographic fronts promote consistent high productivity and prey abundance[27].

Satellite tracking of individual shearwaters indicates that these sites are small in number and located adjacent to Coral Sea mounts and along the eastern edge of the Australian continental shelf in areas where there is likely to be significant localised upwelling (Congdon unpublished data, Figure 14.11).

Such observed linkages between the Coral Sea and southern GBR are significant. These links mean that shearwaters from the Capricorn Bunker island group are reliant on two independent resource bases simultaneously. One of these 'at distance' foraging areas is up to 1000 km from GBR breeding colonies and also appear also to have been impacted by increasing ENSO/sea surface temperature variations over the last decade[92] (Figure 14.2). The breeding success of shearwaters, as well as other seabird species on a regional scale may be totally dependent on the continued stability of a small number of these highly productive areas.

It is possible that these locations also form a major component of the over-winter or non-breeding foraging grounds of wedge-tailed shearwaters and many other seabird taxa. At present little is known about the potential effect of ENSO/sea surface temperature variation on upwelling or productivity at these important foraging refuges, or the effects that any loss in productivity at these locations will have on the wider GBR ecosystem. The conservation significance of such key foraging sites cannot be overstated.

### 14.4.3 Inter-colony movement and breeding

Ultimately, the influence that repeated localised reproductive failures have on seabird populations of the GBR will be determined by the potential for individuals to move elsewhere, or for impacted colonies to be buffered by input from unaffected sites.

Any ameliorating effects of inter-colony movement will decrease as levels of inter-colony gene flow decrease. To date, studies of gene flow and levels of interbreeding among seabirds of the GBR have been equivocal in their results. All detailed molecular analyses have found a lack of observed genetic structuring that suggests high levels of inter-breeding and movement between colonies over broad geographic scales[91,50].

However, these same studies have also demonstrated that a rapid population expansion and colonisation of the GBR by at least some seabirds has occurred in the recent geological past, most likely in association with the appearance of new breeding habitat following the final Pleistocene glacial retreat[90]. Evidence of a recent expansion-colonisation wave implies that measures of contemporary gene flow are confounded by historic associations among populations established during colonisation and are therefore inaccurate[26,90].

In contrast to data indicating high levels of inter-colony gene flow, significant morphological differences have been observed among shearwaters from different colonies that are unrelated to inter-colony distances[93]. These findings suggest some restriction on levels of interbreeding between colonies and the possibility of local adaptation. A lack of inter-colony gene flow is further supported by limited data on the movement of banded birds[87]. For both masked and brown boobies strong breeding colony fidelity has been observed at a regional scale within the broader GBR Coral Sea area, while breeding site fidelity is significantly weaker within smaller localised areas such as the closely spaced colonies of the Swain Reefs[87]. Most extra-limital recaptures of both species were young birds suggesting that only young birds disperse large distances, most likely during their extensive pre-breeding period[87]. Whether they preferentially return to natal colonies to breed is unknown.

Any restriction on gene flow at a regional scale implies that displacement of regional population clusters, such as those in the Swains Reef or Capricorn Bunker Island group, due to climate change impacts will result in permanent loss of those colonies with little chance of re-colonisation from other regional populations improve.

## 14.5 Summary and recommendations

### 14.5.1 Major vulnerabilities to climate change

For seabirds, the key vulnerabilities to climate change are clearly identified as the predicted increases in sea surface temperature and changes to the major seasonal-scale weather patterns that influence circulation and upwelling, such as the ENSO. There are also implications from predicted sea level rise and changes in the frequency and intensity of tropical storms and cyclones, but these potential impacts are not as well understood.

Sea temperature variation is closely linked to ENSO and other types of large-scale oceanographic phenomena, with more frequent and more intense El Niño events producing significantly more variable sea temperatures[61]. Significant detrimental impacts of ENSO related increases in sea surface temperature are already likely to have occurred at all major breeding rookeries throughout the GBR. Principal species known to be effected include three pelagic foraging terns (black noddy, common noddy, sooty tern), and wedge-tailed shearwaters. Other species also likely to have been effected include two booby species (red booby, brown booby) and both frigatebird species (great frigatebird, least frigatebird).

This same group of seabirds have also been impacted elsewhere in the tropical Indo-Pacific, along with other species that breed on the GBR for which no local data are available. Species impacted elsewhere that are known to breed on the GBR include the crested tern, bridled tern, and roseate tern, while other impacted species that breed elsewhere in tropical Australian waters include the lesser noddy, white tailed (*Phaethon lepturus*)[96] and Red tailed tropicbird and Abbott's booby. This list of species constitutes virtually all of the major tropical seabirds breeding on the GBR[56] and encompasses most seabird foraging guilds within the ecosystem. Therefore, it is likely that impacts affecting these species are also affecting GBR species for which limited or no data are available.

Previously, impacts have been observed over long-term (decadal), inter-annual and within-season time scales. The intensity of response to a particular ENSO event is often location specific, with species affected at one location showing different levels of response at other sites. This is likely due to the location specific interactions between changing oceanography and seabird prey availability.

Both in Western Australia and on the GBR, the more pelagic offshore foraging tern and shearwater species were influenced most strongly by oceanographic change, while inshore foraging terns showed a lesser response[111,39]. The more strongly affected species share a number of life-history characteristics. They have larger breeding populations, they are generally synchronous breeders and they feed regurgitated food to young at relatively long intervals, rather than provision young with whole fish more frequently. Consequently, their chicks have longer pre-fledging periods and slower overall growth rates, life-history characteristics that may make them particularly sensitive to ENSO associated fluctuations in food availability.

Based on these findings predicted increases in both sea surface temperature and the intensity or frequency of ENSO events are likely to have serious detrimental impacts on some component of the breeding biology of virtually all tropical seabird species breeding throughout the GBR and in adjacent areas. Importantly, it is likely that breeding populations of at least some species at most significant breeding colonies in the GBR or Coral Sea have already declined due to climate change related phenomena.

### 14.5.2 Potential management responses

With the current level of available information, options for local or regional scale management of climate impacts on seabirds remain very limited. This is because most impacts are directly linked to large-scale global climate phenomena rather than more local threatening processes. In addition, there is a lack of long-term monitoring and associated research studies on seabird population dynamics in tropical and subtropical regions in general, and particularly on the GBR. At present, correlative analysis aimed at detecting potential threatening processes in the GBR rely on general physiochemical data generated independent of any seabird research program and fragmentary population demographic data from just a few principal breeding locations and species.

Managing potential climate change impacts on seabird populations requires identifying general and population-specific causes of observed declines, their associated threatening processes and the functional relationships between these factors. At present only limited data exist about the key foraging locations or foraging modes used by any seabird population of the GBR, or about the direct relationships between oceanographic characteristics and seabird productivity. Without detailed information on foraging areas, resource use and the direct links between seabird reproductive parameters and associated oceanographic variation it is not possible to further identify, predict or adaptively manage climate change or other anthropogenic threats appropriately. Therefore, the principal management response required is to establish comprehensive research and monitoring programs that will fulfil these management needs.

Pelagic seabirds have limited capacity to increase foraging rates. The majority of these species have single egg clutches. This means that in any given season they are either able to rear a chick or not. Therefore, for these species, reproductive viability changes over a small change in productivity or prey accessibility. Thus, climate change stressors are unlikely to produce a slow linear decline in reproductive output. Once productivity is reduced below critical levels breeding colonies fail catastrophically and remain unviable as long as productivity remains low.

Monitoring for slow population declines will not identify potential impending colony failures of this type. Therefore, a management priority needs to identify the rates of change in critical resource levels, the driving processes behind these changes and the species- or colony-specific tipping points at which reproduction is no longer viable. Without these data a broad range of short-term management options are not available prior to colony collapse.

Importantly it must be recognised that impacts to food resources in specific locations, such as in and around known areas of localised upwelling, may have important cascading negative effects over large areas of the GBR. Similarly, based on the current limited information available on inter-colony movement, it must also be assumed that the potential for localised impacts to be buffered by immigration of new breeding recruits from other regions is limited.

Without appropriate data, potential management responses are restricted to attempting to minimise the impacts of other potential or perceived stressors in the system. Whether such measures would be effective is equivocal, since little quantitative data are available linking seabird reproductive output to these phenomena. However, areas for consideration could include the protection of known important forage-fish resources, especially where they overlap with commercial or recreational use, and particularly during ENSO warm years. This may also include increased protection of pelagic predatory fish species such as tuna and mackerel, taxa that seabirds rely on to drive prey species into the surface waters.

Management aimed at minimising general threats could also involve increased protection of breeding sites and/or local foraging resources. This could include limited or no visitation during peak breeding periods, along with recognition that breeding seasons may shift or become extended. These options may be particularly useful to minimise secondary risk at small or threatened colonies.

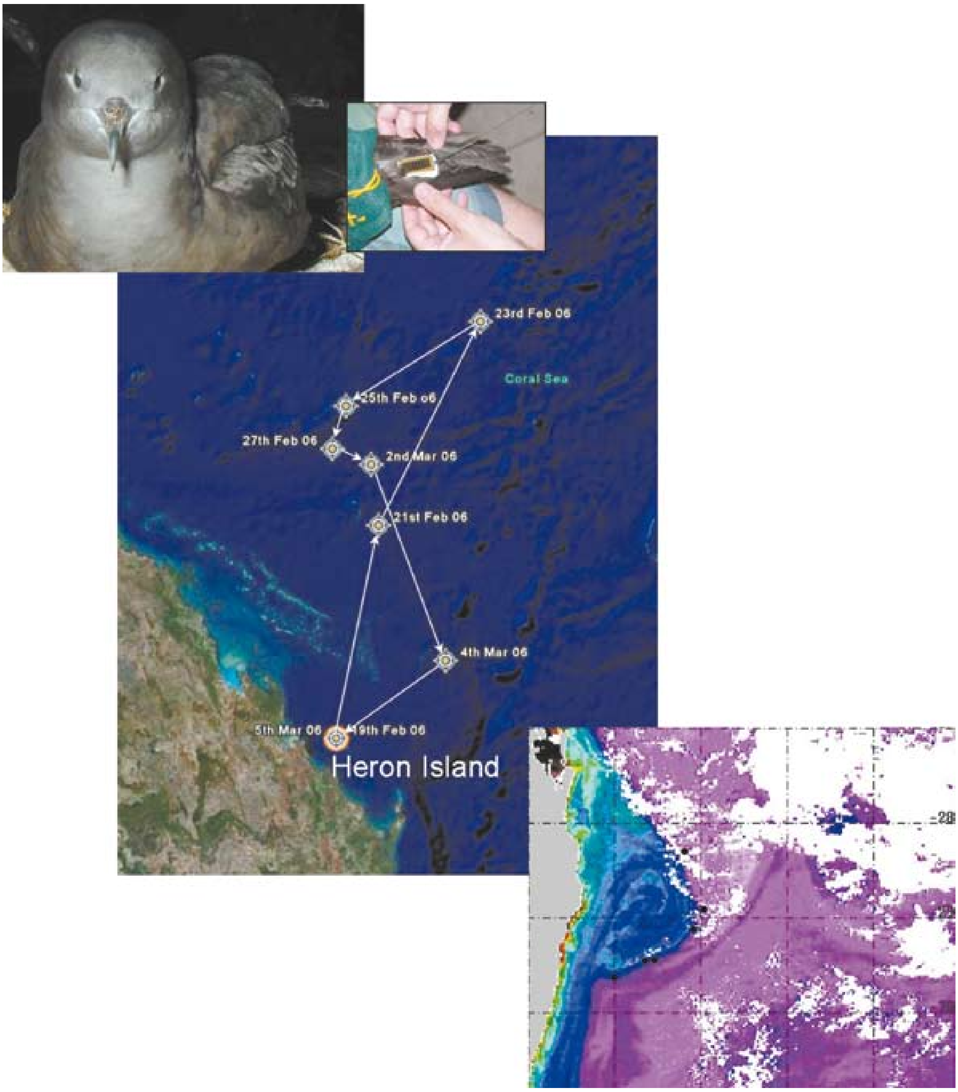
### 14.5.3 Further research

Seabirds are sensitive indicators to changes in forage fish availability and accessibility associated with ENSO and sea surface temperature variation. Therefore, seabird reproductive responses can be used to develop models of, and monitor for, these potential climate change impacts within the GBR.

Platform terminal transmitter type satellite tags (PTT), global position system data loggers and temperature, depth and activity recorders are now routinely and successfully deployed on seabirds of various sizes to link patterns of resource use and foraging behaviour with physical oceanography (Figure 14.11). When combined with information on prey acquisition, provisioning success and satellite imagery on large-scale variation in physiochemical oceanography, these data can be used to identify critical foraging locations, habitat associations and establish trophic relationships that underpin the perceived negative impacts of increases in sea surface temperature.

Ultimately, such data would enable the development of colony-specific predictive models of forage fish distribution and abundance from physiochemical data and permit long-term seabird population viability to be established under alternative climate change scenarios. These are the baseline data needed to determine the types of management options available and how to implement these options in a timely fashion.

***Figure 14.11*** *Example of satellite transmitter tracking of wedge-tailed shearwaters. Photos display a wedge-tailed shearwater fitted with a PTT satellite transmitter. Centre map displays PTT foraging track for a single adult during February to March 2006. Map on lower right displays wedge-tailed shearwater foraging positions (●) along the edge of an oceanographic frontal system off the northern NSW coast (Photo credit: B Congdon, S Weeks)*



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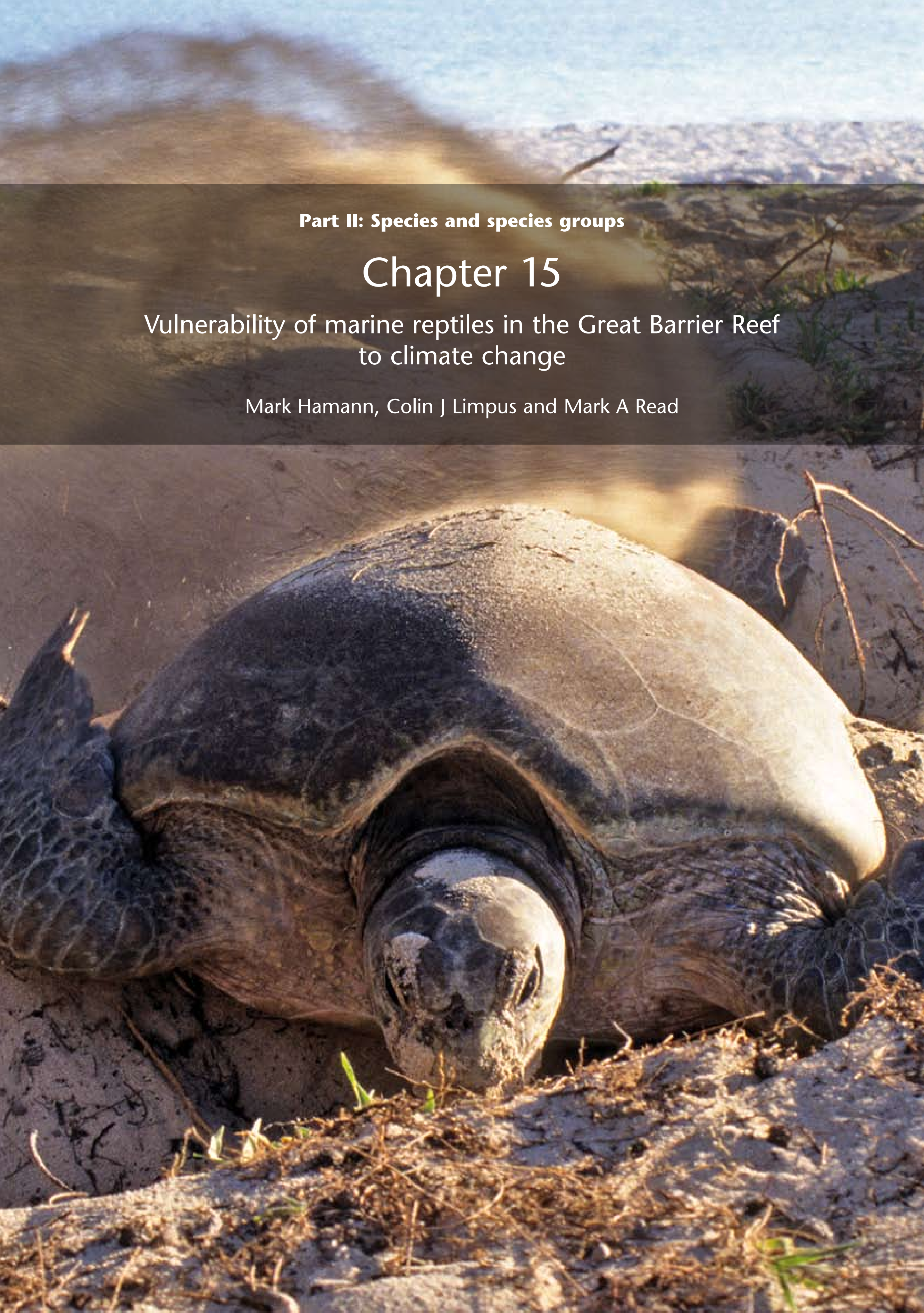
### Part II: Species and species groups

# Chapter 15

## Vulnerability of marine reptiles in the Great Barrier Reef to climate change

Mark Hamann, Colin J Limpus and Mark A Read



## 15.1 Introduction

### 15.1.1 Marine reptiles

Marine reptiles are an important and well-documented component of the Great Barrier Reef (GBR), comprising a single species of crocodile (Crocodylidae), six species of marine turtles (five Chelonidae and one Dermochelyidae), at least 16 species of sea snakes (Hydrophiidae), one species of file snake (Acrochordidae) and one species of mangrove snake (Colubridae). Together these marine reptile species inhabit or traverse through each of the 70 bioregions identified by the Great Barrier Reef Marine Park Authority Representative Areas Program[a]. These marine reptile species, with the exception of some of the snakes, have distributions that span large areas of the GBR. Crocodiles, marine turtles, file snakes, mangrove snakes and sea snakes all have life history traits, behaviour and physiology that are strongly influenced by temperature. All are ectothermic except for the leatherback turtle and thus their body temperatures fluctuate with environmental temperature. For egg laying species (crocodiles and turtles), the temperature of the nest determines incubation period, hatching success and hatching sex ratio. Thus as a group they are potentially vulnerable to climate change.

Extant species of marine reptiles arose from ancient species that existed in the late Miocene or early Pliocene (crocodilians), the Jurassic (marine turtles) and post Miocene (hydrophid sea snakes)[b,10,44,105]. While it is difficult to estimate how long ago today's marine turtle species arose, it was certainly millions of years[105]. Within the southwestern Pacific Ocean sea levels have fluctuated substantially over the last 5000 to 20,000 years and are generally thought to have stabilised around 4000 years ago. While there is evidence of green turtle nesting at Raine Island from around 1100 years ago[79], historical patterns of marine reptile distributions and colonisations prior to European colonisation are not known for the GBR region.

Marine reptile species have persisted through several large-scale climatic and sea level changes that include periods of warming similar in magnitude to patterns predicted for the GBR over the next 50 years (Lough chapter 2). While, quantitative data are available regarding the distribution of marine reptiles within the GBR since the mid 1800s, qualitative data on the abundance, distribution and population sizes of marine reptile species in eastern Australia are only available after the mid- to late-20th century. Hence, there are no precise historical data, or fossil record, to indicate how populations of existing species may have changed, or how they may have coped in relation to historical climate patterns. This is particularly relevant to turtles because 10,000 years ago the GBR region was vastly different. There were no seagrass pastures with foraging turtle herds, nor were there benthic communities of seapens and soft corals to support flatback turtles and none of the currently used nesting beaches were accessible. Hence today's turtles have completely new nesting distribution, foraging distribution and migratory routes. With different climate options, turtles have evolved to cope with climate change in different ways. Green turtles in the Gulf of Carpentaria are winter breeders and thus avoid lethal summer time temperatures on those beaches. In contrast, green turtles breeding along eastern Queensland are summer breeders and avoid the lethal cooler temperatures on the latter beaches. Therefore, we can expect marine reptiles to respond to climate change. However,

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[a] www.gbrmpa.gov.au/corp_site/key_issues/conservation/rep_areas/

[b] Hydrophiid sea snakes arose from the elapids which first appeared in the Miocene

the pertinent contemporary question is how individual populations, or species, would cope with future climate change, given that over the last century there have been widespread increases in the type and scale of anthropogenic impacts to marine reptiles that have depleted several populations and threatened others[44,57,60,113].

In this chapter we provide an overview of the status of the marine reptile species for which there are data, and then assess the vulnerability of these groups to aspects of climate change based on existing ecological and biological data from the three major groups (crocodiles, marine turtles and sea snakes).

### 15.1.2. Overview of the status and distribution of marine reptile species in Queensland

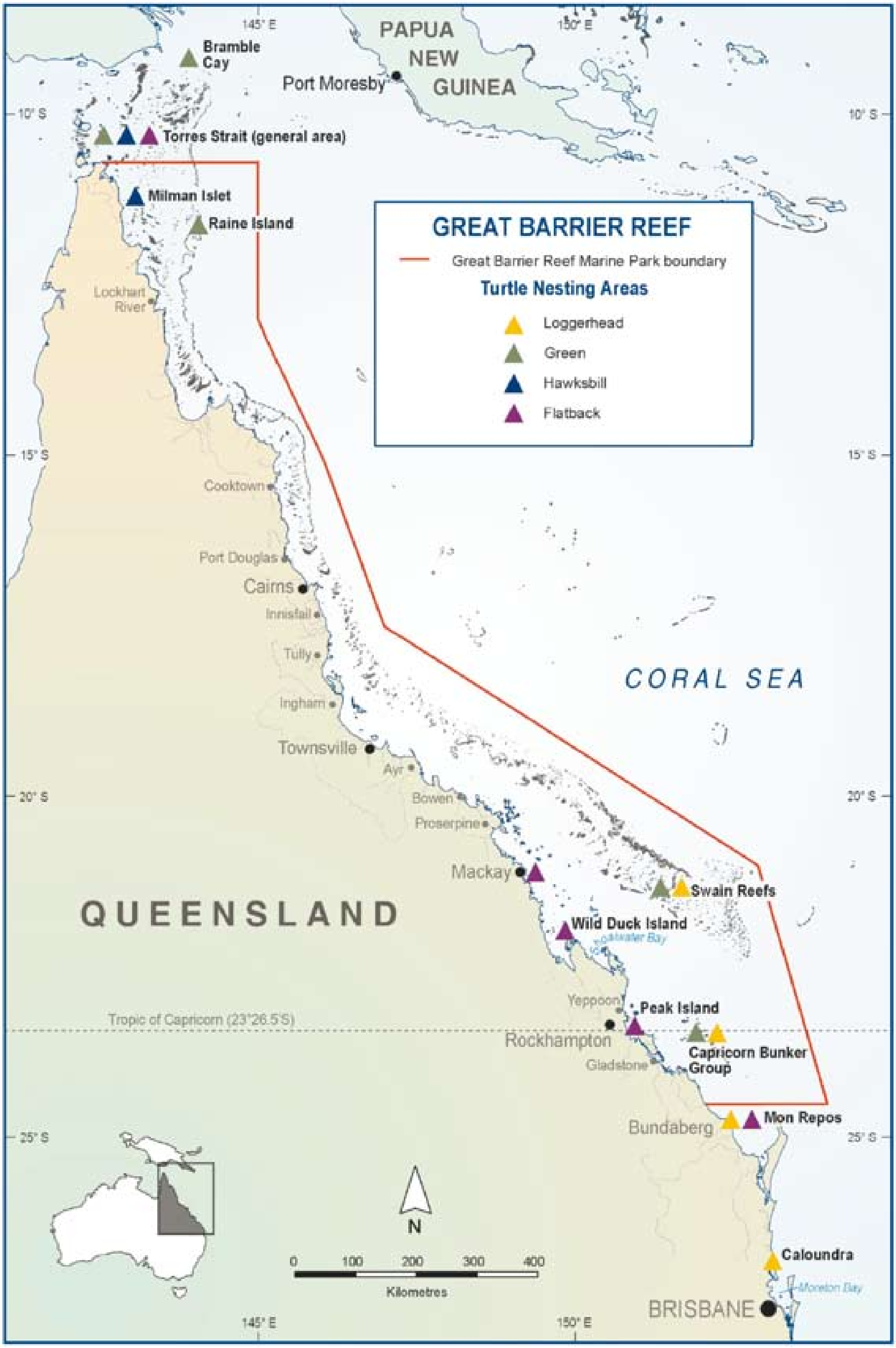
#### Marine turtles

Within the GBR, six species of marine turtle have been recorded foraging and four species have major nesting populations. All six species are listed as threatened under Queensland and Federal legislation, and the International Union for Conservation of Nature and Natural Resources (IUCN) Red List. With the exception of the flatback turtle, each of the six species residing within the GBR is found throughout the world's tropical, sub-tropical or temperate waters[4]. Within Queensland and the GBR the population structure, distribution, range and status of these populations have been reasonably well documented so we will only present a short summary for each species here[22,62,59,76,77,79].

There are three breeding populations in eastern Australia for the green turtle (*Chelonia mydas*), two in the GBR (one in the far northern GBR and one in the far southern GBR – centred around the Capricorn Bunker group of Islands and the Swains Reefs Cays) and one in the Coral Sea Islands[95] (Figure 15.1). Turtles from these three populations are widespread throughout the region from latitudes in central New South Wales (NSW) northwards to Papua New Guinea (PNG) and longitudes from eastern Indonesia east to the south Pacific Islands[41,79,75]. Long-term census data on these populations indicate that although significant declines in population size are not apparent, other biological factors such as declining annual average size of breeding females, increasing remigration interval and declining proportion of older adult turtles to the population may indicate populations at the beginning of a decline[62,79].

The loggerhead turtle (*Caretta caretta*) has a single population in eastern Australia and main nesting sites occur on the islands of the Capricorn Bunker group and mainland beaches at Wreck Rock and Mon Repos (Figure 15.1). Furthermore, loggerhead turtles breeding in Queensland are part of the same genetic population as those from the small nesting rookeries (tens of females per year) in New Caledonia, and possibly Vanuatu[82,64]. Foraging immature and adult turtles from this population are widespread throughout the region from latitudes in central NSW northwards to PNG and longitudes from eastern Indonesia east to the Solomon Islands and New Caledonia[64,65]. In Queensland, the loggerhead turtle population has been monitored annually since the late 1960s and has undergone a substantial and well documented decline in the order of 85 percent in the last three decades[65].

***Figure 15.1*** *Distribution of significant turtle nesting and foraging areas referred to in this chapter*



The hawksbill turtle (*Eretmochelys imbricata*) has a single breeding population in Queensland, for which the nesting areas are spread from the islands in western Torres Strait into the far northern GBR[68]. Within the GBR, Milman Island is the main rookery, and it has been regularly monitored by the Queensland Parks and Wildlife Service (QPWS) since the early 1990s[22,68] (Figure 15.1). There are also many medium- and low-density nesting beaches on islands north of Princes Charlotte Bay. Hawksbill turtles that forage within the GBR migrate to breed in areas throughout the Indo-Pacific region[93]. Annual nesting beach monitoring data from Milman Island collected from 1990 to 1999 indicate that the nesting population has declined by around three percent per annum[22,68].

No breeding of olive ridley turtles (*Lepidochelys olivacea*) has been recorded along the east coast of Queensland[55,57]. Most available information on the distribution of olive ridley turtles are derived from trawler by-catch data collected in the late 1990s by the Queensland Department of Primary Industries and Fisheries. These data show that olive ridleys reside throughout much of the non-reef areas of the GBR[112].

Green, loggerhead, hawsksbill and olive ridley turtles have a common life history trait with hatchlings actively swimming into waters offshore of the rookeries. This is followed by post hatchlings being dispersed by ocean currents out into pelagic waters where they forage on macro-plankton. After variable periods of years in pelagic habitats, these species return as juvenile or sub-adult turtles to coastal waters where they change their foraging strategy to benthic feeding.

The flatback turtle (*Natator depressus*) has a single eastern Australian breeding population centred on rookeries in the southern GBR such as Wild Duck Island and Peak Island[76] (Figure 15.1). However, nesting for this species occurs in low density on many of the mainland and island beaches from Mon Repos north to Cape York[76] (QPWS unpublished data). Foraging turtles from this population are widespread throughout eastern and northern Australia, including southern PNG. Unlike other species of marine turtle in Australia, the distribution of the flatback turtle is generally restricted to the continental shelf, extending into southern PNG and Indonesia[71,121], (QPWS unpublished data). Long term monitoring data collected for the eastern Australian population, from index rookeries at Wild Duck and Peak Island, show no signs of a declining population[76].

During the 1970s and 1980s regular low density nesting of leatherback turtles (*Dermochelys coriacea*) occurred on beaches from Wreck Rock southwards to Mon Repos[66,67,72] (Figure 15.1). Nesting numbers have since declined and no leatherback turtle nests have been reported in Queensland since 1996, despite annual nesting surveys for loggerhead turtles that use the same beaches[40]. This Queensland nesting population has not been analysed to determine genetic relatedness to other regional nesting rookeries such as PNG, Arhnem Land, Indonesia or those of the eastern Pacific (Mexico and Costa Rica)[40]. This species is primarily an oceanic, pelagic foraging species and is rarely encountered in GBR waters.

Marine turtle management within the GBR region over the last 50 years has focussed primarily on: species protection regulations and closures of commercial harvesting protecting most of the nesting areas for each species within eastern Australia under the *Nature Conservation Act 1992*, protecting large areas of their marine habitats within Federal and State managed multiple-use marine parks, controlling foxes on mainland beaches to reduce egg loss through predation, regulating trawl and net fisheries (using temporal and spatial closures and mandatory use of turtle excluder devises), reducing boat strike incidences and rescuing doomed eggs at risk from flooding or erosion.

## Estuarine crocodiles

Two species of crocodile occur in northeastern Australia, the estuarine crocodile (*Crocodylus porosus*) and the freshwater crocodile (*Crocodylus johnstoni*). Only estuarine crocodiles are recorded within the GBR and the neighbouring coastal zone. Estuarine crocodiles were intensively hunted from the mid 20th century until they were protected by legislation in 1974. These extensive harvests severely depleted wild populations and subsequently estuarine crocodiles are listed under Queensland State and Australian Federal legislation as vulnerable and endangered under the IUCN Red List.

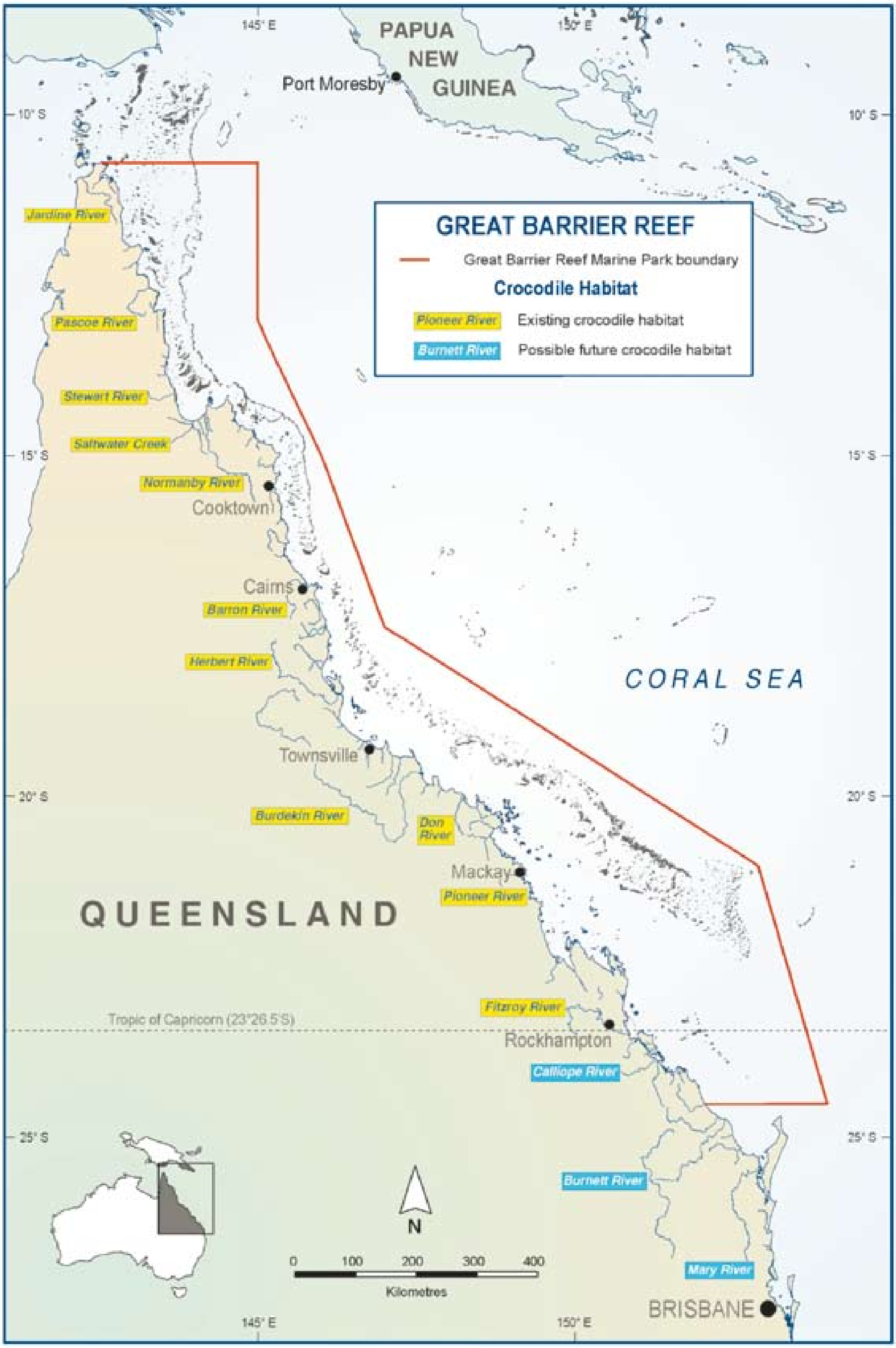
The distribution and abundance of estuarine crocodiles within the GBR and adjacent coastal zone has been well documented[89,109]. In eastern Queensland, estuarine crocodiles occur from Torres Strait, southwards to Gladstone[109] (Figure 15.2), although sightings have been reported as far south as the Gold Coast. Genetic studies indicate that estuarine crocodiles along the east coast of Queensland are not panmictic, hence there are limits to gene flow, and variance in alleles indicates population structure along the east coast of Queensland has occurred (Nancy FitzSimmons pers comm). Read et al.[109] and Taplin[122] distinguish eight biogeographic regions for estuarine crocodiles in Queensland. Five of these lie along the east coast and include overlap with the GBR. Although the spatial distribution of estuarine crocodiles varies significantly between the biogeographic regions, population densities in the east coast catchments (including the Burdekin and Fitzroy River catchments) are low (see Figure 15.2 for location of catchments). Within the GBR estuarine crocodiles have been recorded from many of the inshore islands in northern areas[89]. While no estuarine crocodile nesting sites have been recorded within the GBR, nesting has been recorded along sections of the coastal fringe (eg the western side of Hinchinbrook Island)[89,109]. Crocodiles found in the GBR are primarily immature sized individuals coming out of adjacent rivers. Therefore the GBR crocodile population is not self-sustaining, it is ephemeral, but dependent on the functioning of the populations in adjacent rivers.

Crocodile management within the GBR region over recent decades has focussed primarily on: species protection regulations and closure of commercial harvesting, protecting large areas of their marine habitats within Federal and State managed multiple use marine parks, removal of problem crocodiles that threaten public safety.

## Sea snakes

There are two groups of sea snakes found in Australia – Hydrophiidae and Laticaudidae. The Hydrophiidae are the only species of sea snakes to have breeding populations in the GBR. There are at least 16 species of Hydrophiid sea snake residing within the GBR[44]. While the broad distributions of most of the species have been documented, abundance estimates are only available for a few species, or for restricted sections of the GBR, and there are no data on which to base status assessments[44]. Eleven species of sea snakes are endemic to Australian waters but none of these are endemic to the GBR. No species of sea snake found in Australian waters is listed as threatened under Queensland or Australian legislation or by the IUCN. However, sea snakes are considered a ‘listed marine species’ under Australian Federal legislation and are protected species under the *Nature Conservation Act*, *Queensland State Marine Parks Act* and the *Great Barrier Reef Marine Park Act*. The high diversity of sea snake species within the GBR reflects a high diversity of micro-habitats that are used by the group. These range from coral reefs to shallow soft bottom habitats to deeper open water habitats[44]. While most are benthic foraging species, one species, *Pelamis platurus*, is primarily a pelagic foraging species in oceanic waters.

**Figure 15.2** *Distribution of current and potential crocodile habitats along the east coast of Queensland*



Sea snake management within the GBR in recent decades has focused primarily on: species protection regulations and closure of commercial harvesting, protecting large areas of their marine habitats within Federal and State managed multiple-use marine parks.

## 15.2 Vulnerability of marine reptiles to climate change

### 15.2.1 Ocean circulation

The post hatchling phase of the marine turtle life cycle was initially coined the 'lost years' because, it was suspected that hatchlings made their way offshore through coastal and offshore oceanic currents, and little was known about dispersal routes, or aspects of their ecology during their oceanic dispersal phase[13,20,56,129]. Through mapping the occurrence of post hatchling turtles coupled with the use of genetic techniques and oceanic current modelling it appears that loggerhead and southern GBR green turtle hatchlings from Queensland rookeries disperse via offshore currents such as the East Australian Current and its eddies. Dispersal patterns for hawksbill and green turtles in the northern GBR are not known. Flatback turtles remain on the continental shelf and do not have an oceanic life stage[125].

Recent population models indicate that oceanic stage green and loggerhead turtles return to coastal foraging areas at around five to ten years and 10 plus years respectively[16,18,65]. Although there are few empirical data on the finer scale movements and diet of turtles during the pelagic stage, or the specific factors that influence delivery of individual turtles to benthic foraging areas, it is likely that these factors are reliant upon currents. Hence, changes to ocean circulation can potentially influence (positive or negatively) the ecology of post hatchling and juvenile turtles. However, due to the uncertainty in predicting how ocean circulation may alter with climate change (Steinberg chapter 3) it is difficult to predict in detail how marine turtles will be affected (positively or negatively) by shifts in the ocean currents over the next 50 years.

### 15.2.2 Changes in water and air temperature

Temperature is one of the most pervasive variables affecting biological and developmental processes and thus it asserts a strong selective pressure, especially on ectotherms. Animals vary in their sensitivity to environmental temperatures and can be generally classed within two main thermal boundaries, eurytherms, which can operate at a wide variety of body temperatures and stenotherms, which can operate over a narrow range of body temperatures[2]. Marine reptile species fall in different positions within these broad groups, and their positions vary depending on life stage.

For example, estuarine crocodiles generally stay within, or close to, particular catchments and are exposed to seasonal fluctuations in temperature. To regulate their body temperature within an optimal range they use a variety of behavioural and physiological mechanisms such as basking and other behavioural patterns. Moreover, their ability to vary behavioural and physiological attributes on daily and seasonal cycles enables them to function very well in tropical regions and over a wide range of seasonal temperature variations[119]. For marine turtles, while juveniles and adults can function in a range of environmental temperatures while at sea, adult females can overheat while on land for nesting and the successful development of embryos and the determination of hatchling sex occurs

within a definite thermal range[79,91,120] (Figure 15.3). In this section we assess the vulnerability of marine reptiles to increases in air and sea surface temperatures by 2050 of 1.9 to 2.6°C and 1.1 to 1.2°C respectively (Lough chapter 2).

### *15.2.2.1 Exposure – temperature*

In this section we assess the probability and magnitude of exposure of marine reptiles to increased air and sea temperatures.

#### Marine turtles

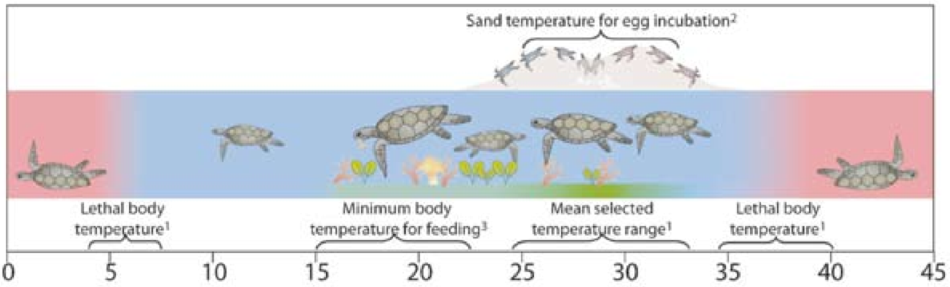
There is a high probability that exposure to changes to increased air and sea surface temperatures will affect marine turtles in two broad areas, reproduction and foraging ecology.

#### *Reproduction and reproductive timing*

Marine turtles are seasonal breeders and the frequency of breeding varies both within and between species[36,89]. Females of each species are capital breeders, meaning that they accrue the energy needed for reproductive events prior to breeding[36,50]. The actual time it takes to develop enough somatic energy stores to begin, maintain and complete the vitellogenic or spermatogenic cycle is dependent on a combination of food availability, food quality, digestive processes and migration distance (from foraging to breeding)[4,5,11].

The timing of seasonal reproductive events in marine turtles is most likely controlled by a complex system involving genetically entrained energy thresholds and numerous metabolic and endocrine pathways[37,38,39]. Put simply, there are several key decisions that need to be made by an adult turtle with regard to reproductive cycles, such as whether or not to begin spermatogenesis or vitellogenesis or to remain quiescent, when to migrate to the breeding area, and when to cease breeding and migrate back to the foraging area[35]. The results of each of these decisions will rely upon a combination of co-dependent proximal and ultimate cues, such as body condition and environmental factors (eg sea temperature and photoperiod). However, because marine turtles from particular breeding populations come from foraging grounds spread over large geographic areas it is likely that reproductive cycles are linked to a combination of photoperiod and ability of the animal to detect

***Figure 15.3*** *Operating temperature parameters for marine turtles. MBTF represents minimum body temperature for feeding (except leatherback turtles); MSTR represents mean selected temperature range (Data sources: 1 Spotila and Standora[120], 2 Miller[91], 3 Read et al.[107])*



changes such as temperature rises[35]. Moreover, the changes in air and sea temperature are not likely to be uniform over the entire GBR, or indeed throughout the ecological range of the species, with changes likely to be greater in higher latitudes (ie southern GBR, Lough chapter 2). Therefore, while marine turtles will be exposed to increases in air and sea temperature over their range, they will be exposed to differing degrees, and changes will occur at different scales. Consequently, it is difficult to predict the magnitude of exposure for particular species or populations.

There are two general patterns of seasonal nesting for marine turtle breeding in Queensland, dry season (winter to spring) nesting occurs in the Gulf of Carpentaria, western Cape York and western Torres Strait and wet season (summer) nesting occurs in central Torres Strait and along the entire eastern coast of Queensland. Rookeries in this latter group have seasonal peaks of nesting with occasional low density nesting in the 'off season' and in southern Queensland rookeries there is virtually no 'off season' nesting. Within a season female turtles lay multiple clutches of eggs, and each species has a definite peak of nesting[22,36,77].

### *Clutch incubation and embryo development*

The successful incubation of turtle eggs relies on sand temperatures during incubation being between 25 and 33°C[91]. On nesting beaches located along the east coast of Queensland, sand temperatures within this range generally occur between November and March, with highest temperatures generally occurring in January and February. Hence there is a high probability that projected increases in air temperature of 1.9 to 2.6°C by 2050 (Lough chapter 2) will result in sand temperatures during the Austral summer consistently reaching the upper end of, or exceeding, the narrow thermal window for successful egg incubation at most current marine turtle rookeries with resulting increases in egg mortality. In addition, altered sex ratios are likely to ensue.

### *Foraging area dynamics and reproductive periodicity*

Predictions on how invertebrate (mollusc, crustacean, sponge or cnidarian), benthic communities will respond to climate change are based on limited data (Hutchings et al. chapter 11). Hence it is speculative to predict whether climate change impacts on invertebrate groups may in turn impact on nutritional ecology of carnivorous/omnivorous marine turtle species. In contrast, for the herbivorous green turtle increased sea temperatures at foraging areas will impact the distribution, abundance and health of seagrass and algae and these trophic factors are likely to have flow-on impacts for turtles residing in particular habitats (Diaz-Pulido et al. chapter 7 and Waycott et al. chapter 8).

Foraging area impacts (positive or negative) are more likely to occur for green turtles because the interval between breeding seasons of this species is resource dependent[6,11], and the number of females breeding in a particular year is correlated with an index of El Niño[69,70]. Although mechanisms that underlie this relationship remain unclear, Chaloupka et al.[18] suggested that dietary ecology was the link, based on studies that demonstrated that growth rates of green turtles residing at particular foraging areas vary according to local environmental stochasticity. Therefore, based on available evidence from turtle breeding patterns and information presented in chapters 7 and 8 of this volume, it is likely that the dietary ecology of green turtle populations will be sensitive to changes in water temperature because of temperature related changes to seagrass and algal communities.

### Estuarine crocodiles

*Reproduction*

Miller and Bell[89] provide a review of estuarine crocodile distribution in the GBR World Heritage Area, and nesting site preferences and distribution of nesting sites in Queensland are described by Magnusson[85] and Read et al.[109]. Crocodile nesting has been recorded in coastal zones of the GBR such as Hinchinbrook Island[89] with limited nesting habitat existing in the catchments between Cairns and Rockhampton[49,109]. Predicted levels of climate change will expose nesting sites to increased air temperatures. Exposure of nesting sites to increased temperatures will influence estuarine crocodile population dynamics because, the sex ratio of hatchlings is temperature dependent and temperature plays an important role in embryo development, incubation time and can influence the phenotype of hatchling estuarine crocodiles.

*Distribution and abundance*

The spatial distribution and abundance of estuarine crocodiles along the coast of Queensland is highly variable[109,122]. Along eastern Queensland highest densities of estuarine crocodiles occur north of Cooktown, and lower population densities found south of Cooktown were attributed to a lack of suitable nesting habitat and decreasing average air temperatures in the southern latitudes[49,109,122]. The southernmost breeding populations of estuarine crocodiles occur within the Fitzroy River, near Rockhampton in central Queensland[109] (Figure 15.2). Although satellite tracking studies indicate that estuarine crocodiles can move considerable distances within river systems, over land, and into the adjoining coastal zone[108] there are few data on factors that influence dispersal and habitat choice for estuarine crocodiles (eg sex/size related shifts in dispersal patterns and habitat choice). However, it is possible that with continued recovery to the populations and increased air and sea temperatures in central and southern Queensland there could be a southwards expansion in the range of estuarine crocodiles concomitant with increased densities in coastal streams. If there are population increases in streams adjacent to the southern GBR, then there is a reasonable probability that there will be increased numbers of immature crocodiles occurring in southern GBR waters.

### Sea snakes

All species of hydrophiid sea snakes that reside within the GBR are truly marine and do not come onto land at any stage of their life cycle. Maintenance of body temperatures in sea snakes depends on water temperature, and because of their small surface area to mass ratio, it is difficult for them to raise their body temperatures above their surroundings[44]. Even dark coloured snakes at the surface can only increase body temperatures by around 3°C[43]. Therefore, sea snakes will be exposed to changes in sea temperature. However, there is little known about the fine scale distribution of different species, thermal requirements, thermal tolerances, fine scale aspects of dietary ecology (ie prey selectivity), or how preferred prey items will be influenced to assess their vulnerability to the projected rises in sea temperature of 1.1 to 1.2°C by 2050.

## *15.2.2.2 Sensitivity – temperature*

In this section we assess the magnitude and direction of response to levels of increased temperature on marine reptiles.

## Marine turtles

Marine turtles are likely to be adversely affected by increases in air temperature by 1.9 to 2.6°C by 2050. This time frame is approximately one to two generations for the four species that breed in the GBR, green[17], loggerhead[46,64,65], flatback (QPWS unpublished data) and hawksbill turtles[16,68].

### *Reproduction: clutch incubation and embryo development*

All species of marine turtles are oviparous. Within a breeding season, a female will lay multiple clutches of eggs on beaches above the high water mark. Embryo development takes around eight weeks and the incubation period is strongly correlated with sand temperature[1,92]. The successful development of marine turtle embryos occurs within a well defined temperature range of 25 to 33°C[91]. Arguably, the most substantial impact of temperature on marine turtle life history in the short term (one to two generations which equates to 60 to 80 years) is during the embryo development phase.

There are volumes of empirical studies that demonstrate the interactions of temperature and embryo development in marine turtles, and many studies that investigate temperature-dependent sex determination (TSD) (Box 15.1). The determination of sex in marine turtles depends on sand temperatures during the middle third of the incubation period, with cooler and warmer temperatures producing a higher proportion of males and females respectively[28,90]. The constant incubation temperature at which 50 percent males and females are produced is termed the pivotal temperature or $TSD_{50}$[31,74,96]. Pivotal temperatures based on laboratory experiments have been determined for green and loggerhead turtles nesting in eastern Australia and generally fall between 27 and 30°C. Pivotal temperatures may vary between and within species or even within populations of the same species[74,97].

### **Box 15.1** *Temperature dependent sex determination*

Not all vertebrate species determine sex of offspring in the same way. Many animals use genotypic sex determination in which the factors that determine sex are contained in sex chromosomes. This method of sex determination occurs in all vertebrate families. A second method of sex determination is phenotypic, in which the sex of offspring is not determined during conception rather it is determined after fertilisation and is dependent on incubation temperatures. This method of sex determination is commonly referred to as temperature dependent sex determination (TSD) and it occurs in all crocodilians, the tuatara and some turtles (including all marine turtle species), lizards and fish[123]. There are three recognised patterns of TSD – (TSD II) female-male-female in which females are produced at high and low temperatures, (TSD IA) male-female in which males and females are produced at low and high temperatures respectively and (TSD IB) female-male in which females and males are produced at low and high temperatures respectively[123]. In each of these patterns offspring sex is determined during a limited thermosensitive period during incubation. Recent work has demonstrated that during the thermosensitive period temperature initiates a suite of endocrinal pathways that act on the differentiation of gonads[9,27,103].

The determination of natural sex ratios for populations or rookeries is difficult because sand temperatures are not constant throughout the incubation period and they may vary greatly within and between particular rookeries, or beaches, for a population[42,74,97]. While laboratory studies can determine pivotal temperatures, and different models based on natural nest temperature profiles can allow gross prediction of sex ratios at individual rookeries[29], numerous proximate environmental and

geographical factors dictate sand temperature profiles at a population level. For example, sand type and colour, beach location (island or mainland), aspect and shading from vegetation and climatic events such as frequency of rainfall and cloud cover are likely to play a role in ensuring that a mixture of both sexes are produced from each rookery and for each population[7,42,90,97].

Since field based TSD studies began on marine turtles in the early 1980s there have been numerous studies conducted on sex ratios from beaches throughout the world and researchers have commonly reported female biased sex ratios. However, given that archival temperature data loggers have only become readily available in the last 15 years, plus the logistical and financial constraints of conducting multi year and multi rookery projects, most field based studies on TSD and sex ratios have been short (one to three years) and have been rookery focused rather than population focused. To get a better understanding of how sex ratios may change throughout ecologically relevant temporal and spatial scales, longer term studies at population level are warranted[30,42]. While such studies are needed within the GBR, there is sufficient knowledge about species population boundaries, some nesting beach characteristics (eg sand colour), nesting seasonality and baseline sand temperature data for marine turtle species breeding in the GBR to indicate that populations will be sensitive to increased air temperatures of 1.9 to 2.6°C by 2050.

*Foraging area dynamics and reproductive periodicity*

Marine turtles reside along the entire coast of eastern Australia, though only the leatherback turtle, which is rarely encountered within the GBR, is recorded regularly south of Sydney (latitude 33 °S)[40,62]. However, eastern Australia (eg Moreton Bay north into Torres Strait) provides some of the most important and protected foraging habitats for marine turtles along Australia's east coast, and indeed the Indo-Pacific region. While each of the five species that forage in the GBR has different habitat and dietary requirements and physiological tolerances that limit micro-habitat use, they are found throughout the latitudinal range (14 degrees) of the GBR[62,112]. Most knowledge on distribution, abundance and species ratios in particular areas come from mark-recapture studies managed by Queensland Parks and Wildlife Service, tag returns from Indigenous hunters, the public or commercial fishers and the Queensland Department of Primary Industries and Fisheries trawler by-catch studies in the late 1990s[112]. Presumably, within the GBR the strongest effect temperature has on the life history of individual species of marine turtles while in foraging areas is through its effect on physiological processes, food availability or quality (see chapters 7, 8, 9, 10 and 11 for vulnerability of algae, seagrass, mangroves, corals and benthic invertebrates).

Green turtles are essentially herbivorous in the wild. They are an important component of seagrass, mangrove and algal habitats and feed mainly on seagrasses, algae and mangrove leaves[6,63]. Capture-mark-recapture data from QPWS indicate that green turtles show strong site philopatry to a particular foraging area, and in Queensland it does not appear that they undertake developmental migrations[81,98]. Furthermore, when forage conditions are compromised in particular areas, such as after cyclones or floods, green turtles stay in the general area trading-off the risks of movement with declined growth rates[17,18]. Given a broad distributional range coupled with high site fidelity it is likely that green turtles will be exposed to changes in sea temperature at varying degrees throughout their range. It remains difficult to estimate how sensitive the species will be to increased water temperature at foraging areas until more is known about the finer scale links between temperature and its influence on food availability, dietary processes, growth and reproduction.

Loggerhead turtles are carnivorous and in southern Queensland they have been found to feed mostly on a variety of crustaceans and molluscs. Moreover, diet composition differs spatially, and is presumably dependent on the distribution and abundance of prey items and individual preferences[78]. The diet of hawksbill turtles has not been described in Queensland. However, hawksbill turtles in the Northern Territory have a mixed diet of algae and sponges[130]. Leatherback turtles mainly forage in open water on jellyfish, but outside the GBR. Less is known about the diet of both olive ridley and flatback turtles. They are presumed to be carnivorous feeding primarily on a range of crustaceans, molluscs and soft bodied benthic invertebrates such as holothurians[6].

There is a growing body of literature on the impacts of climate related factors on seagrass and coral habitats as well as the biology or community ecology of marine invertebrates[45,54,104,117] (chapters 7, 8, 9, 10 and 11). While it is often difficult to provide causal links between aspects of climate with changes to biological and/or ecological attributes in marine ecosystems, results generally suggest that marine invertebrates and habitats such as seagrass and coral reefs are sensitive to factors such as increased water temperature, changes in ultraviolet radiation and carbon dioxide ($CO_2$)[3,54,106] (chapters 7, 8, 9, 10 and 11). However, there is likely to be complex interplay of various environmental factors that underpin spatial and temporal effects within species and community levels. Therefore, although it is likely that changes to air and sea temperatures will effect marine habitats and community structure there is not enough data on specific habitat requirements, or on the precise impacts temperature will have on the distribution, abundance and population structure of seagrass species and marine invertebrates to predict how sensitive marine turtle species will be to climate change over the next 50 to 100 years.

In addition, for ectothermic species such as chenoniid turtles, changes to ambient temperatures can bring about changes in the rates of chemical reactions that underpin physiology. Therefore, with rising water temperature, it is not inconceivable that growth rates may be enhanced and hence age to maturity may decrease or the size at which first breeding occurs may be larger, rates of fat deposition or yolk storage into ovaries (vitellogenic cycle) may increase and hence shorten the intervals between breeding seasons. If the types of physiological change required to underpin these life history traits occur then progressive warming of their habitats will have positive benefits with regard to sea turtle population dynamics.

### Estuarine crocodiles

#### *Clutch incubation and embryo development*

Estuarine crocodiles are oviparous, and while few data exist on breeding rates in the wild, in captivity most females do not breed annually[48]. Within a breeding season a female estuarine crocodile will make a mound nest during the wet season and lay a single clutch of around 40 to 60 eggs[113]. Eggs take around 90 days to hatch[113]. The determination of sex in hatchling estuarine crocodiles is dependent on the mound nest temperature. In general, crocodilian mound nest temperatures are between 30 and 33°C[86], and metabolic heating can increase nest temperatures by 2 to 3°C[25, 29]. Webb et al.[127] report a female/male/female pattern in which no males are produced at temperatures below 29°C and above 34°C and varying percentages are found in the intermediate temperatures. Moreover, these authors also demonstrate that the sex of the embryos was determined within approximately 17 to 52 days (19 to 58 %) after the start of incubation.

*Temperature influence on behaviour and physiology*

Estuarine crocodiles are large reptiles, and as ectotherms their internal heat production is negligible. Hence, they generally thermoregulate by using behavioural mechanisms to exploit their thermal environment[118]. In particular, estuarine crocodiles use a combination of atmospheric and aquatic basking, shade seeking, postural adjustments, and changing orientation (reviewed in Grigg and Seebacher[33]) to regulate temperatures to within a narrow range. The importance of water temperature and basking behaviour in estuarine crocodiles for thermoregulation, and consequences for the maintenance of physiological processes and behaviour is becoming increasingly apparent[118]. Furthermore, data derived from experimental studies demonstrates that the sustained swimming speed of juvenile estuarine crocodiles increases in warmer waters (23 to 33°C compared with 15°C) and then decreases as water temperatures rise above 33°C[24]. However, while estuarine crocodiles will be sensitive to increased water and air temperatures associated with climate change, this sensitivity should be seen in the context of them being a tropical species that occur along the equatorial zone of South East Asia.

### Sea snakes

There is little known about the thermal requirements and tolerances of individual species of sea snakes, hampering assessment of their sensitivity to projected rises in sea temperature of 1.1 to 1.2°C by 2050. However, *Pelamis platurus* is the most widespread of the sea snake species and its distribution has been empirically linked to sea surface temperature patterns[23]. Distribution of *P. platurus* is linked to thermal zones, and has upper and lower thermal tolerances of between 36.0 and 11.7°C[23,32]. It is likely that other sea snake species have a thermal range within the boundaries of those of *P. platurus*.

*Seasonal reproduction in marine reptiles*

The cycles and physiological mechanisms that underlie ovarian and spermatogenic processes have been well reviewed in marine turtles, but less information is available for estuarine crocodiles and sea snakes[36,51,99]. Each of the four marine turtle species that breed in eastern Queensland have summer nesting seasons. Estuarine crocodiles breed in early summer and clutches are laid during the summer wet season[111]. In contrast, although less data are available, it appears sea snakes have reproductive cycles and gestation periods that vary in length and timing both within and between species, although they generally culminate with young being born in late summer and autumn[12,44,53]. There are not enough data to indicate what factors underlie the variation in reproductive cycles in sea snakes and this area warrants further attention.

Reptiles have large pineal glands; indeed marine turtles have one of the largest pineal glands per body size of all vertebrates[100]. It is therefore generally believed that the timing of reproductive events in marine turtles and other reptiles is determined by a combination of photoperiod and temperature that act via melatonin to interact in the hypothalamus with other endongenous cues to tell the animal the appropriate time for breeding[35,38,99]. The proximate and ultimate cues that underlie reproductive cycles and allow synchronous breeding within a population are not well studied in marine reptiles. This area warrants further attention before estimates can be made of how sensitive reproductive cycles are to climate change.

### *15.2.2.3 Impacts – temperature*

*Temperature-dependent sex determination*

#### Loggerhead turtles

There are several potential impacts of increased air and sea temperature on the incubation and sex determination of marine turtle embryos. Indeed, some thermal influences are evident in loggerhead turtles at Mon Repos where sand temperature data has been collected from nest depths since 1968. Since 1997, sand temperatures at nest depth have been commonly recorded above 34°C for weeks at a time[61]. Consequently, sand temperatures exceed the temperature at which 100 percent female hatchlings are produced, and often exceed the upper limit for successful incubation. This is significant because although loggerhead turtles nest on the white coralline sand islands of the southern GBR, and scattered nesting occurs on the white sand beaches south of Fraser Island, the dark coloured beaches of Mon Repos and Wreck Rock support around 70 percent of nesting for the population[65] and produce mostly females. To monitor the magnitude of exposure to high and increasing sand temperatures at a population level, systematic sand temperature collection is needed at all main rookeries and a selection of peripheral ones. Only through the collection of thermal data from incubation environments can longer-term impacts at a population level be predicted.

#### Marine turtles in general

Temperature data from most rookeries in Queensland are not yet sufficient to imply how sensitive particular rookeries or populations are, or the degree of impact faced from increases in air temperature over the next 50 to 100 years. Studies that have been conducted in the GBR highlight a need for routine monitoring of sand temperatures at all main and peripheral rookeries for each species[7,8,47,68,80,81]. In particular there are few baseline sand temperature data available for green and hawksbill turtle beaches in the far northern GBR and Torres Strait.

There are insufficient data to indicate what degree of female bias a population of marine turtles can sustain. However, population models have implicated incorrect hatchery procedure, and the subsequent production of a highly skewed female sex ratio in the demise of the Malaysian leatherback turtle population[14]. Based on available data for Queensland, and predictions of warming over the coming 50 years, we speculate that ratios above one male to four females are possible for many GBR rookeries and these ratios (in terms of female bias) may not be sustainable.

*Other temperature related factors*

In addition to effects on sex determination, increased sand temperatures have been found to decrease the incubation time of eggs of all marine turtle species[91]. Hatchlings raised in warmer nests with shorter incubation times have lower residual yolk reserves at hatching[7]. In addition, clutches incubated at temperatures near the upper limits for incubation survival (33°C) result in hatchlings with higher rates of scale and morphological abnormalities[87,91,116]. Laboratory experiments demonstrated that incubation temperature and incubation environment have an effect on swimming performance with hatchlings raised in higher temperature nests, or from nests placed in hatcheries having decreased swimming ability over a six hour period[116,124]. Therefore high, but sub-lethal, temperatures could have a profound impact on hatchling phenotype, health, condition and performance.

### Estuarine crocodiles

#### *Clutch incubation and embryo development*

The influence of incubation temperatures on various aspects of embryo development and hatchling phenotype has been well investigated in crocodilians, although not always for estuarine crocodiles[110]. In short, incubation temperatures have been demonstrated to influence hatchling morphology, pigmentation, thermal responses, locomotive performance, feeding responses and growth[110]. However, there are few threshold data to develop a precise understanding of how increased air temperatures will impact estuarine crocodiles at all levels of biological organisation.

#### *Temperature influence on behaviour and physiology*

The behaviour, physiology and distribution of estuarine crocodiles in the GBR and its catchments are closely linked to temperature. Grigg et al.[34] report that captive estuarine crocodiles in a naturalistic setting maintained modal body temperatures of between 25 and 28°C in winter and 28 to 33°C in summer. However, there are few data on environmental temperatures (water and air) for wild foraging sites, and how these temperatures vary daily, seasonally and with micro-habitats. Hence, it is difficult to identify specific impacts that rises in air temperature by 1.9 to 2.6°C over the next 50 years will have on crocodiles. Additionally, temperature, along with other environmental cues such as rainfall, affects the degree and timing of nesting. In particular, high water levels and cool conditions late in the dry season are the key stimuli required for courtship and mating[48,84,126]. Hence changes in when these environmental cues occur, or the magnitudes to which they occur, may lead to changes in the timing of reproductive events.

### Sea snakes

The optimum temperature ranges for most species of sea snake are unknown. However, if they have a similar upper thermal limit to *P. platurus* (36°C) then it is possible that gradual shifts in range will occur over the course of the next 50 to 100 years.

## *15.2.2.4 Adaptive capacity – temperature*

### Marine turtles

There are likely to be two main autonomous adaptations to cope with increased temperatures and inundation of nesting sites. Firstly, a shift in the start, end and peak of the nesting season to coincide with cooler temperatures and secondly, a shift in the main nesting beaches used[61]. An overall shift in the timing of the nesting season is a possible scenario, and one that has been documented in seasonally breeding birds[19] and for the loggerhead turtle population that nests along Florida's Atlantic coast. In this loggerhead turtle population, Weishampel et al.[128] found that between 1989 and 2003 the median nesting date for the population became earlier by around 10 days. The authors further speculate that this change in nesting seasonality is driven by increased sea surface temperature in adjacent waters[101,128]. However, in eastern Australia turtles that nest in a particular population come from a variety of regionally dispersed habitats, and these habitats will experience variable magnitudes of climate change influences. Therefore, the large-scale coordination required for phenological shifts of a nesting season may take a longer time frame, (ie generations) to develop. In most cases this would also be hard to detect without substantial increases in monitoring effort because subtle shifts would only be detectable at rookeries that have close to saturation monitoring of the nesting beach and high site fidelity of turtles.

Distinct population boundaries exist for marine turtles because female turtles exhibit natal homing, that is, when they reach maturity and begin breeding they return to the region of the beach where they hatched[83,88]. After the first breeding season female turtles exhibit strong site fidelity and most females will return to the same rookery to lay clutches within seasons and in each of their subsequent seasons[38,83,92]. It is unclear what mechanisms female turtles use to select a nesting site, but they are able to shift between beaches in a particular area, and readily do. For example, in the 1977 season at Heron Island and Wreck Island 2.2 to 9.2 percent of green turtles and 3.9 to 7.9 percent of loggerhead turtles were previously recorded nesting on another island earlier in the season (islands within about 100km of each other)[72]. In addition, tagging data from the 1998–1999 season show that 6 percent and 1.6 percent of the 8156 green turtles recorded nesting in east coast rookeries shifted nesting beaches between and within seasons respectively[21]. Ability for female turtles to shift between rookeries both within and between seasons could be one mechanism that enables populations to endure changes to nesting habitats that prevent or restrict nesting or clutch success.

For loggerhead and green turtle rookeries in southeast Queensland, detecting and monitoring changes in the numbers of turtles using particular nesting beaches would be relatively easy to detect given the strong public interest in marine turtles and high public visitation during the summer months. In comparison, because rookeries for hawksbill, flatback and green turtles in the northern GBR are remote and infrequently visited, the detection of changes in the phenology or fidelity will be difficult to document until relatively large shifts have occurred. However, while slow change will be hard to detect, longer-term changes in nesting distribution will be detectable because the distribution of nesting has been well mapped in Queensland.

### Marine turtles

#### *Foraging behaviour*

It is not known what mechanisms influence the initial choice of foraging location. It is important to note that capture-mark-recapture studies on several species in Queensland indicate that turtles found at a particular foraging location as a juvenile retain that site as their foraging location for life, and very seldom do turtles switch locations[80] (QPWS unpublished data). It is therefore possible that shifts in foraging location or habitat selection within a location will be altered if there are substantial negative changes to forage pastures.

### Estuarine crocodiles

Behaviour, physiology, reproductive timing and reproductive output of crocodilians and alligators are linked to temperature[34,52,119]. From a behavioural and physiological perspective, estuarine crocodiles have an optimum body temperature range they adjust via thermoregulatory behaviour, metabolism and cardiovascular responses to match daily and seasonal changes in environmental temperature[34,119]. Indeed, mathematical approaches such as that used by Seebacher et al.[119] could be adapted to predict changes in thermoregulatory patterns with increases in environmental temperatures.

Estuarine crocodiles are opportunistic breeders and the frequency and timing of reproductive events is largely determined by temperature. While there are few data available for wild populations of estuarine crocodiles, American alligators have adapted to varying environmental conditions throughout their range by having different onset of breeding seasons in northern and southern ends of their range

and reaching sexual maturity at a younger age in warmer climates[52]. Therefore, estuarine crocodiles have behavioural and physiological attributes that will allow them to adapt to projected temperature rises by 2050.

#### Sea snakes

There is insufficient information on thermal sensitivity of individual species of sea snake to estimate how particular species will respond to increased sea temperature. Potential changes could include changes in distribution of certain species and/or their prey, timing of movements and reproductive events.

### *15.2.2.5 Vulnerability and thresholds – temperature*

If climate change were operating alone, at the forecasted levels, there would be minimal risk of localised (population) extinction for each of the groups, especially marine turtles and crocodiles, over the next 50 to 100 years. However, the question of how depleted or recovering populations (eg loggerhead turtles and estuarine crocodiles) cope with climate change in the longer term in addition to other pervasive threats remains unanswered. For example, a southwards shift in nesting distribution is one proposed coping mechanism that loggerhead turtles could undertake[61]. This could have the impact of shifting the main nesting beaches out of the protected zone of Mon Repos (latitude 24.80° S) to more developed beaches such as those on the Sunshine Coast (eg Caloundra – latitude 26.80° S). Consequently, a whole new suite of issues for management agencies will arise. Currently, the small numbers of nests laid on the beaches of Caloundra are monitored and once fox predation is curtailed it is believed that these nests should function well (QPWS unpublished data). For the northern GBR green turtle population the impacts of climate change need to be assessed with consideration for existing threats such as decreased hatchling production, illegal fishing, overseas village harvests and traditional Australian take. Similarly, for estuarine crocodiles, much of their habitat south of Cooktown has been encroached by urban or agricultural development. Hence, any changes in the animal's behaviour, southwards shift in distribution, or higher abundance will need to be seen in light of possible increased human-crocodile interactions.

## 15.2.3 Changes in ocean chemistry

Ocean pH is expected to decrease by between 0.15 and 0.25 by 2050. There are no available data to indicate whether ocean acidification would have any affect on marine reptiles in the GBR. Since ocean acidification is a result of changes to carbonate buffering, if any direct impacts were to be found they would most likely occur during neonatal life stages when individuals are developing skeletal structure. In addition, it is possible that indirect effects through ecosystem linkages could occur. However there is insufficient data from which to draw speculation on sensitivity or specific impacts.

## 15.2.4 Changes in light and ultraviolet radiation

The most likely impact that light and ultraviolet (UV) changes will have on marine reptiles is through disturbance to food chains, especially for the herbivorous green turtle. As detailed by Diaz-Pulido et al. (chapter 7) and Waycott et al. (chapter 8) most macroalgae and seagrass species in the GBR will be influenced by changes in the quality or quantity of light. However, the impacts to seagrass and algae from pervasive light reductions may be highly variable between and within species and ultimately depends on each plant species minimum light requirements and tolerance to changing light. The condition, distribution and abundance of some seagrass and macroalgae species are inextricably linked to the diet, growth and reproductive output of green turtles. Conversely, these habitats are strongly influenced by the size of the foraging herd, and the herd's dietary ecology. However, given the uncertainty in light and UV predictions (Lough chapter 2), and a lack of data about direct effects on the nutritional and dietary ecology of green turtles, it is hardly possible to evaluate the potential sensitivity and vulnerability of green turtles to changes to light and UV.

## 15.2.5 Sea level rise

There is high confidence that sea level in the GBR will rise by 7 to 38 cm and 13 to 68 cm by 2020 and 2050 respectively. This rate of increase could be even greater if the recently observed rapid melting of the Greenland ice sheet continues (Lough chapter 2).

### *15.2.5.1 Exposure – sea level rise*

In this section we assess the probability and magnitude of exposure of marine reptiles to sea level rise.

#### Marine turtles

Marine turtles will be exposed to changes in sea level through the impact these rises will have on nesting beach stability. The four species of marine turtles that nest in, or in close proximity to, the GBR use beaches with different physical characteristics (Table 15.1).

***Table 15.1*** *Main nesting areas for marine turtles in the GBR*

| **Flatback turtles** | **Continental islands of the central GBR** |
|---|---|
| Loggerhead turtles | Coral cays of the Capricorn Bunker group and Swains Reef in the southern GBR and the mainland beach at Mon Repos and Wreck Rock |
| Green turtles (southern population) | Coral cays of the Capricorn Bunker group and the Swains Reef |
| Green turtles (northern population) | Coral cays of the far northern GBR, and Torres Strait (Bramble Cay) and islands in Torres Strait (Murray Island group) |
| Hawksbill turtles | Inner reef cays of the far northern GBR and central Torres Strait |

Nesting populations span a variety of beaches that often have very different thermal profiles[74], and differ drastically in the number of nests per kilometre[68,73]. Turtles are well able to change beaches within and between breeding seasons. If nesting habitat is unsuitable turtles can be expected to shift, especially for young adults choosing their first beach. When this happens a degraded nesting beach could be effectively abandoned within one generation. A pertinent question is whether turtles will respond to changed temperature or sea level in relation to nesting beach choices. In essence, because sea level rise will affect some islands, cays and beaches to different degrees based on a suite of physical characteristics (Smithers et al. chapter 21) it is not possible to estimate the degree to which each of the species will be affected.

### Estuarine crocodiles

Estuarine crocodiles are likely to be exposed to the predicted rise in sea level through effects on low-lying rubble cays, mangrove forests and salt marshes (Turner and Batianoff chapter 20 and Smithers et al. chapter 21). It is also probable that sea level rise will influence the reach of the estuarine zone and expose current nesting sites in low lying areas of catchments.

### Sea snakes

Sea snakes have a low probability of exposure to increased sea level. However, there could be indirect effects to reef species if the fish communities they rely on for food are impacted by sea level rise.

## *15.2.5.2 Sensitivity – sea level rise*

In this section we assess the magnitude and direction of response to levels of sea level rise on marine reptiles.

### Marine turtles

Marine turtle nesting areas will be exposed to sea level rise to varying degrees. In the short term (next 50 years) it is most likely that the effects will be most predictable and noticeable at rookeries that have had long-term marine turtle monitoring programs, including Raine Island, Heron Island (and other Cays in the Capricorn Bunker Group), Mon Repos, Milman Island, Peak Island, Wild Duck Island and Bramble Cay. However, over the longer-term (more than 50 years) sea level rise may help other coral cays to develop and/or stabilise (Turner and Batianoff chapter 20) and thus other nesting sites may become available, or become better suited to providing an incubation medium. Alternatively, sea level rise may remove available nesting habitat and the remaining sites might not be suitable because of human uses such as established coastal development. However, mainland beaches are within the range of the existing inter-nesting change of rookery that is currently used by southern GBR turtles[21], and human activities can be managed.

## *15.2.5.3 Impacts – sea level rise*

### Raine Island – marine turtle rookery

There are seven main nesting rookeries for the northern GBR green turtle population, the largest green turtle population in the world, of which Raine Island and Moulter Cay receive over 90 percent of nesting female turtles. Over the last 10 years it has become apparent that hatchling success of clutches laid at Raine Island is poor, and in some years virtually no hatchlings are being produced from the rookery[79,81]. The most compelling argument as to why this is occurring is that the beach system is being eroded, and hence there are fewer suitable nest sites and nests are more exposed to inundation by the freshwater table and salt water from wave intrusions[79,81]. Whether or not the erosion of beach dunes has been accelerated due to blasting of the reef for construction of a guano mining facility, or a natural coral cay process is unknown. Regardless of the underlying reason, predicted sea level rise is likely to accelerate the erosion process and the frequency of nest innundation.

### *15.2.6 Physical disturbance – tropical storms*

While the intensity of tropical cyclones in Queensland is likely to increase, there is limited confidence in the precision of the estimate with regard to spatial and temporal variability (Lough chapter 2). Increased frequency or intensity of tropical storms will affect marine reptiles to varying degrees. However exposure is likely to vary both spatially and temporally.

#### Marine turtles

There is substantial empirical and anecdotal data on the impacts of tropical storms on marine turtle nesting beaches throughout the world. In general, most authors report aperiodic, localised and seasonal effects on nesting beaches which consist of changes to beach profile or inundation of incubating nests with sea water, and rarely does a storm effect all beaches for an entire population[58,94,114,115]. However, several factors influence the formation, path, longevity and severity of tropical cyclones. Therefore it is not possible to predict the likelihood of exposure to, or potential impacts on marine turtle populations in the GBR. For example, severe cyclones passing over non-critical habitat or at non-peak nesting times may have less of an impact than low intensity cyclones passing directly over key nesting areas at peak nesting times. Furthermore, the magnitude of adverse effects are difficult to predict because they depend on the intensity and timing of the cyclone (with regard to turtle nesting seasons), frequency of cyclones, tidal influences and the size of storm surges and proximity of the cyclone to the nesting beaches.

#### Estuarine crocodiles

Since the distribution of estuarine crocodiles residing on islands within the GBR is patchy and low density, estuarine crocodiles residing on islands are likely to have a low probability of exposure to, and impact from, aperiodic tropical storms. However, for estuarine crocodiles in estuarine and freshwater rivers along the east coast of Queensland, especially breeding areas, there will be a moderate probability of aperiodic, localised and seasonal effects from cyclones because of localised flooding. Such events are likely to include washing away of nests or nest material, inundation of eggs and disruptions to normal nest attendance behaviour during flood events.

### 15.2.7 Rainfall and river flood plumes

There is low confidence in the predictions for changes in total rainfall that correlate with frequency and intensity of river flood plumes as a result of climate change. Total rainfall may increase in the southern and northern GBR but may decrease in the central GBR. If this is the case, then small-scale river flood plumes may increase in the southern and northern GBR but decrease in the central GBR (Lough chapter 2). Increased rainfall could potentially affect the timing and success of reproduction in estuarine crocodiles and marine turtles and the foraging ecology of marine turtles and potentially sea snakes.

#### Marine turtles

One aspect of marine turtle nesting behaviour that is linked to rainfall is the ability of a female turtle to successfully complete digging a nest and laying eggs. One common reason that female turtles abandon nesting attempts is a failure to be able to dig a body pit and egg chamber in loose dry sand. For most GBR turtle rookeries on coral cays nesting success in an average year would be expected to be in the order of 50 to 80 percent[22,35]. Indeed, at Bramble Cay in the Torres Strait nesting success increased

from less than 70 percent to greater than 90 percent after the onset of consistent wet season rainfall[77]. However, in drier than average years, dry sands coupled with high density nesting at some rookeries can lead to rates of nesting success of less than 10 percent[79,81]. Female turtles that make repeated unsuccessful nesting attempts throughout a season run the risk of prematurely depleting energy stores and therefore need to reduce energy use in order to have sufficient energy to fuel homewards migration[37]. In addition, increased rainfall helps to reduce the occurrence of potentially lethal fungi on incubating marine turtle eggs[102]. However, the influence of rainfall on marine turtle nesting biology is ultimately dependent on spatial and temporal variations in rainfall events. There is not enough precision in rainfall estimates for the next 50 years, or the likely temporal and spatial variability of these estimates to indicate how vulnerable marine turtles will be to increased rainfall. It is, however, likely to remain an aperiodic factor that shapes intra- and inter-annual variation in nesting success and embryo development.

#### Estuarine crocodiles

The number of female crocodiles breeding in a particular year, and the timing of reproduction events such as nesting, are closely related to climatic events in the later part of the dry season[126]. In general, higher than average rainfall (ie higher water levels) at the end of a dry season coupled with cool temperatures will trigger mating and courtship[48,84]. However, while this relationship has been found in a limited number of populations, it has not been explored in Queensland populations and it is likely to have spatial and temporal variability over the latitudinal range of the species. Further, rainfall or temperature thresholds that underlie the reproductive behaviour are unknown and thus it is not possible to comment on how vulnerable estuarine crocodiles are to changes in rainfall. Rainfall is, however, likely to remain an aperiodic factor that shapes intra- and inter-annual variation in reproductive periodicity, reproductive success and embryo development.

#### Sea snakes

There are insufficient data on water quality requirements for sea snakes to determine whether or not increases in rainfall will have any impacts on sea snakes.

## 15.3 Linkages with other ecosystem components

Collectively, marine reptiles reside in, migrate through or breed in a large variety of habitats, or bioregions identified within the GBR Marine Park[26]. Broad scale ecosystem components such as seagrass meadows, coral reefs, islands, mainland beaches, mangroves, estuaries and freshwater systems are especially important for marine reptiles, yet there are substantial gaps in understanding the specific roles of marine reptile species in the ecosystem. Moreover, there is recognition that the ecological roles of marine reptile species may vary both temporally (including ontogenetic and seasonal shifts) and spatially (including latitudinal variation and variation between genetically distinct populations) and their roles are shaped by variation in climatic events.

### 15.3.1 Constraints to adaptation

Although few data are compiled on the biological traits of many sea snake species, there is a growing base of knowledge on population dynamics, distribution and abundance of estuarine crocodiles and marine turtles in eastern Queensland. These two groups of reptiles include slow growing, long-lived species with delayed maturity. Both groups have experienced large-scale variation in climate over thousands of years and have life history traits that enable them to endure aperiodic climatic events that threaten seasonal reproductive output. Consequently, in the temporal and spatial context of this assessment, out to 2050 and 2100, and for the GBR, the current constraints for adaptation are life history traits (eg slow growth, low reproductive output and high egg and hatchling mortality); declining (hawksbill turtles), depleted (loggerhead turtles) and recovering (estuarine crocodiles) populations; anthropogenic threats (coastal development, agriculture, hunting, incidental capture in fisheries or bather protection programmes, boat strike and marine debris); and restricted alternative nesting sites.

### 15.3.2 Interactions between stressors

For each of the marine reptile groups there are numerous stressors to population function that have only recently (ie within one to two generations) been managed. Stressors include the commercial hunting of estuarine crocodiles in Queensland, fisheries based interactions, coastal development and agriculture, predation by introduced wildlife, Indigenous hunting within Australia and overseas, natural mortality and climate related impacts. Given that for many of these stressors it is difficult to gain estimates of their magnitude, and their spatial and temporal variability, it is difficult to make specific statements about interactions. However, because there are numerous stressors, including numerous climate related stressors, the cumulative impact may be significant. The recent green turtle population model developed by the Great Barrier Reef Marine Park Authority and the Queensland Environment Protection Agency[15] could be used to predict consequences of climate related impacts such as changes in sex ratio, or increased nest failure in relation to other stressors. Remediation of stressors to marine reptile populations within the GBR will need to involve a whole of government approach to develop a series of tools aimed at reducing the impact individual stressors, and crucially their cumulative effect, may have on marine reptiles.

### 15.3.3 Threats to resilience

The primary threats to resilience of climate related impacts vary for each of the marine reptile groups, species and populations. In general, marine reptiles include long-lived, slow to mature species. Each group faces a variety of anthropogenic threats throughout their range and in some cases populations have undergone substantial declines over the last 30 to 40 years. Therefore, the main threat to resilience for marine reptiles is the cumulative impact of multiple stressors on a particular species, and these threats vary in magnitude temporally and spatially for each species.

## 15.4 Summary and recommendations

### 15.4.1 Major vulnerabilities to climate change

This chapter has highlighted that the major vulnerability for marine reptiles to climate related events is to increased air and sea temperatures. Each of the marine reptile groups comprise tropical or sub-tropical species that are adapted for life in warmer climates and they have historically experienced time periods of warmer temperatures and vastly different coastal geomorphology. However, the contemporary question is how these species will cope with increased temperature in conjunction with numerous other threatening processes. Essentially if average seasonal sand temperatures at marine turtle nesting beaches consistently rise above 30°C they are likely to impact embryo development through alterations to sex ratios (in favour of females), phenotype or through direct mortality. If they consistently rise above 33°C alterations to the success of embryo development and changes to the phenotype of emerging hatchlings are likely. Increased temperatures are likely to have a similar impact on the incubation of estuarine crocodile eggs, but the thresholds are more difficult to quantify. Likely responses to these impacts include shifts in the timing of the nesting season and shifts in nesting locations (this could also arise from sea level rise).

Marine reptiles will be exposed to increased water temperature, and increased ambient temperatures are likely to alter rates of physiological and biochemical processes. Consequently, increased water temperatures could exert a positive influence through increased growth rates, increased reproductive output and changes to distribution and abundance.

Marine turtles are vulnerable to sea level rise. However, while the magnitude and direction will vary both among and between species, some rookeries will be more sensitive than others. For example, there are both anecdotal and empirical reports of long-term erosion at several important marine turtle rookeries in the Torres Strait (eg Bramble Cay), the far northern GBR (eg Raine Island) and the Capricorn Bunker group (eg Heron Island). Hence these rookeries will be particularly susceptible to increased sea level rise and turtles can be expected to shift their nesting distribution. Therefore, managers need to plan for protection of future potentially important nesting beaches (eg resilience of beaches to climate for turtle nesting reasons).

Marine reptiles, especially estuarine crocodiles and marine turtles are vulnerable to shifts in the frequency and intensity of storms, El Niño, rainfall and flood events. Since there is uncertainty on how each of these factors will change over the next 50 years it is difficult to predict the magnitude and direction of the effect. However, they are all likely to continue to be aperiodic shapers of seasonal reproductive output for marine reptile species in the GBR.

### 15.4.2 Potential management responses

#### Marine turtles

*Protection at nesting beaches from increased temperature*

Shading of incubating nests, or the relocation of clutches into cooler zones (ie under trees), has been used as a management tool by wildlife agencies in several countries (eg Malaysia). However, these shading and relocation programs have tended to be associated with hatcheries, or on small rookeries (less than 500 nests per season). Similar programs could be established in some GBR rookeries, however, the costs of developing and maintaining a similar program at larger rookeries have not been examined but are likely to be very resource (money and labour) intensive.

*Identification of the cause of poor hatchling success at Raine Island*

A concerted effort should be taken by management agencies to identify the cause(s), and possible solutions to the sand loss and poor hatchling success at Raine Island. This will take a coordinated approach including marine turtle ecologists, native title holders, wildlife managers, coastal geomorphologists, coastal engineers and other stakeholders interested in the preservation of the islands biological, historical and cultural values.

### Estuarine crocodiles

*Manage human-crocodile interactions*

Estuarine crocodiles are opportunistic foragers and breeders, and along eastern Queensland much of their habitat has been encroached upon by urban and agricultural development. Any changes to distribution, abundance, density or behaviour of estuarine crocodiles, whether related to climate changes or not, may alter current risk of human-crocodile interactions occurring. The Queensland Parks and Wildlife Service has a statutory plan and procedural guidelines that relate to the classification, management and removal of problem estuarine crocodiles. In addition, the QPWS assess the risk of human-crocodile interactions using a standard framework for identifying the likelihood and consequences of these interactions[c]. Regular standardised surveys for estuarine crocodiles within coastal catchments[109], and regular communication with water users, land holders and other stakeholders needs to be continued to monitor any changes in the likelihood and consequences of human-crocodile interactions.

## 15.4.3 Further research

*Increased monitoring of current and future marine turtle sites*

Monitoring programs at key foraging and nesting areas for each of the marine turtle species in the GBR should be continued. Monitoring programs should be expanded and refined to include aspects such as beach and air temperatures at a population scale, and designed to determine shifts in nesting sites or season length.

*Risk assessment of climate change threat to populations of marine turtle and estuarine crocodiles*

Research activities that focus on determining the risk to particular species are warranted, and these should include (but not limited to) determining current and future exposure to environmental temperature, impacts on reproductive output, distribution (nesting and foraging) and possible alterations to existing threats from human interactions.

*Investigate impacts of increased temperatures on estuarine crocodile reproduction and distribution*

Research activities that aim to assess nest and hatchling distributions, clutch success, breeding rates and temperature effects in wild nests are warranted. This information would provide strong empirical support for any future climate related vulnerability assessment.

*Determine distribution, abundance and ecological status of sea snake species*

One clear outcome of this vulnerability assessment is that there are substantial gaps in our knowledge on the distribution, abundance, population structure, diet and reproductive ecology of sea snakes. Future research on sea snake ecology and conservation status is warranted.

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[c] principles outlined in AS/NZS4360:2004 Risk Management

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**Part II: Species and species groups**

# Chapter 16

## Vulnerability of marine mammals in the Great Barrier Reef to climate change

Ivan R Lawler, Guido Parra, Michael Noad

## 16.1 Introduction

### 16.1.1 Scope of chapter

Throughout this volume the reality and general nature of climate change impacts have been reiterated and thus we do not do so here. Our focus in this chapter is to relate how those impacts, and the flow-on consequences of them, will manifest in changes to habitats and food resources that in turn may affect the marine mammals of the Great Barrier Reef (GBR).

The marine mammals of the GBR are an ecologically diverse group (Table 16.1). They possess some important similarities in terms of life history and basic physiology that make general interpretations of their vulnerability to some impacts appropriate. These similarities are:

- they are mammals, and thus air breathing and endothermic, consuming relatively large quantities of food relative to body size in comparison to fishes and invertebrates, and
- they are long-lived and slow breeding so are susceptible to low levels of mortality, particularly of breeding adults.

However, in other aspects of their ecology, such as diet and movements, they differ sufficiently that we have addressed them separately. For these purposes, we have made the general distinction between dugongs, dolphins, and whales (Table 16.1). Note that 'dolphins' refers to members of the family Delphinidae, including some of the toothed whales (such as killer whales). 'Whales' includes baleen whales, sperm whales and the little known beaked whales. Where substantial differences between species within these groups exist, and there are sufficient data on these differences, we address these separately.

Our conclusions about the impacts of climate change on most (if not all) marine mammals of the GBR are tentative and speculative due to: i) uncertainty about the magnitude and direction of the impacts of climate change on the GBR, and ii) our overall lack of knowledge about the ecology of most marine mammals in the GBR. However, the information presented identifies areas of concern for these species under climate change and highlights the importance of gathering baseline ecological data on marine mammals in the GBR.

### 16.1.2 Significance of marine mammals in the GBR ecosystem

Marine mammals are significant in the GBR in ecological, cultural and economic contexts. There are particular legal obligations to protect marine mammals under the federal *Environment Protection and Biodiversity Conservation Act*, the *Great Barrier Reef Marine Park Act 1975* and the *Queensland Nature Conservation Act 1992*.

Whales in particular support active tourist industries via whale watch boats for dwarf minke whales in the northern GBR and humpback whales in the Whitsundays. One commercial dugong watching operation also exists but this is a relatively small scale and infrequent operation. There is no commercial dolphin watching within the GBR. However significant dolphin-feeding tourism occurs for bottlenose dolphins in Moreton Bay and, to a lesser extent, for Indo-Pacific humpback dolphins in Tin Can Bay in the Great Sandy Straits. Dolphins from these populations may range within the GBR.

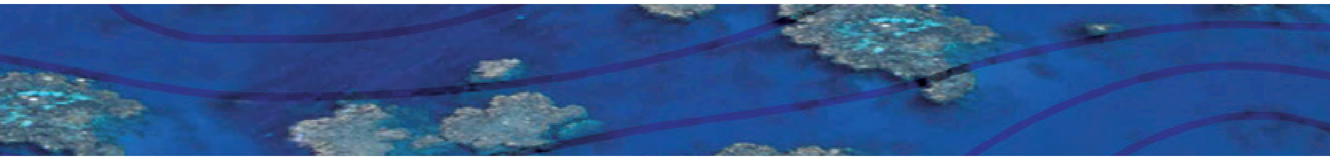

***Table 16.1*** *Marine mammal species known or suspected to occur in the GBR*[a]

| Group | Family | Common Name | Scientific Name |
|---|---|---|---|
| Dugongs | Dugongidae | Dugong | *Dugong dugon* |
| Dolphins | Delphinidae | Australian snubfin dolphin | *Orcaella heinsohni* |
| | | Bottlenose dolphin* | *Tursiops spp.* |
| | | False killer whale | *Pseudorca crassidens* |
| | | Fraser's dolphin | *Lagenodelphis hosei* |
| | | Indo-Pacific humpback dolphin | *Sousa chinensis* |
| | | Killer whale | *Orcinus orca* |
| | | Long beaked common dolphins | *Delphinus capensis* |
| | | Long-finned pilot whale | *Globicephala melas* |
| | | Melon headed whale | *Peponocephala electra* |
| | | Pantropical spotted dolphin | *Stenella attenuate* |
| | | Pygmy killer whale | *Feresa attenuata* |
| | | Risso's dolphin | *Grampus griseus* |
| | | Rough-toothed dolphin | *Steno bredanensis* |
| | | Short beaked common dolphins | *Delphinus delphis* |
| | | Short finned pilot whale | *Globicephala macrorhyncus* |
| | | Spinner dolphin | *Stenella longirostris* |
| | | Striped dolphin | *Stenella coeruleoalba* |
| Whales | Physeteridae | Sperm whale | *Physeter macrocephalus* |
| | Kogidae | Dwarf sperm whale | *Kogia simus* |
| | | Pygmy sperm whale | *Kogia breviceps* |
| | Ziphidae | Blainville's beaked (or dense beaked) whale | *Mesoplodon densirostris* |
| | | Cuvier's beaked whale | *Ziphius cavirostris* |
| | | Longman's beaked whale | *Mesoplodon pacificus* |
| | | Strap-toothed (Layard's) beaked whale | *Mesoplodon layardii* |
| | Balaenopteridae | Dwarf minke whale | *Balaenoptera acutorostrata subsp.* |
| | | Fin whale | *Balaenoptera physalus* |
| | | Humpback whale | *Megaptera novaeangliae* |
| | | Sei whale | *Balaenoptera borealis* |
| | | Blue whale | *Balaenoptera musculus* |
| | | Pygmy blue whale | *Balaenoptera musculus brevicauda* |
| | | Bryde's whale* | *Balaenoptera edeni* |
| | | Antarctic minke whale | *Balaenoptera bonaerensis* |

* The distinctive forms and relationships of these species are still unresolved and more than one species/subspecies may occur within the GBR.

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[a] Modified from: Great Barrier Reef Marine Park Authority[25]

Dugongs also have special cultural significance for Indigenous people with hunting being an activity closely associated with Indigenous culture[31]. Dugongs were also cited as one of the World Heritage values of the GBR[24].

The ecological roles of marine mammals are largely determined by their diet and the effects of their feeding on the food resources. As these are the areas of greatest difference we address them separately for the three groups.

#### *16.1.2.1 Significance of dugongs*

Dugongs are specialist seagrass feeders that feed predominantly on fast-growing, low-biomass pioneer species such as *Halodule* and *Halophila*[40]. Feeding by dugongs has been shown to affect the community composition of seagrass beds such that it favours pioneer species at the expense of slower growing climax species[4]. Feeding by dugongs also affects the chemical composition of seagrass species with re-growth of both *Halophila* and *Halodule* showing, for example, higher whole plant nitrogen concentrations up to a year after grazing[5]. Chapter 8 (Waycott et al.) on seagrasses describes the multitude of fauna and flora that are dependent on various seagrass species. Thus, the effect of dugong grazing may carry through to a wide range of taxa and communities, particularly where dugongs are abundant.

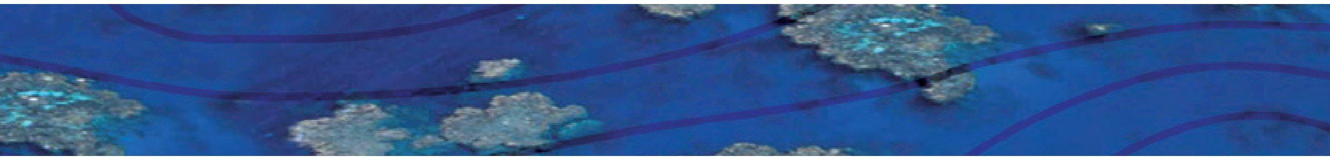
It is difficult to quantify just how important this role is, or should be, for dugongs. The population in the GBR has been substantially reduced since at least the 1960s. In some areas, reflected by the location of Dugong Protection Areas along the urban coast of the GBR, dugong densities are high and we might expect them still to have a significant structuring effect on seagrass communities. Marsh et al.[43] hind-cast the population for Queensland south of Cairns based on an index of the rate of population decline and the present day population estimate. They then used an estimate of the carrying capacity of the GBR south of Cairns, itself based on estimates of seagrass areas and productivity, to constrain the upper bounds of the dugong population estimate. Their estimates ranged between 31,000 and 165,000 (upper and lower 95% confidence limits), but they concluded that the lower estimate was more consistent with present day seagrass resources. This contrasts with a present day estimate for the same area of approximately 4500 dugongs.

#### *16.1.2.2 Significance of dolphins*

Delphinids (family Delphinidae) represent a unique component of marine biodiversity. They are the most diverse and widespread of marine mammals, and the only mammals (together with whales and dugongs) that live their entire lives at sea. In addition delphinids represent one of the most socially diverse and complex groups of mammals, and have evolved cognitive and communication abilities found only in few mammalian species.

Sixteen species of delphinids are estimated to occur within the waters of the GBR (Table 16.1), ranging from the coastal medium sized and potentially endemic Australian snubfin dolphin (*Orcaella heinsohni*) to the large, offshore and widespread killer whale (*Orcinus orca*).

Most dolphin species in the GBR feed on patchy resources of fishes and cephalopods found throughout the water column in estuarine and marine environments. As large, mobile marine vertebrates in high trophic levels, dolphins have the potential to profoundly affect their prey populations, which in turn



may result in significant influence on food-web interactions (ie trophic cascades), and ecosystem function and structure. Similarly, decreases in the availability or abundance of dolphin prey may have strong influences on dolphin distribution and abundance. Examples of such interactions and their ecological consequences include: i) depletion of krill and silverfish by minke whales, killer whales and Adélie penguins[1]; and ii) increase of planktivorous fishes in the Black sea due to decreases in abundance of pelagic predators (dolphins, mackerel, bonito, bluefish) caused by overfishing[20].

For most species occurring in the GBR, information on some of the most basic ecological (distribution, abundance, movement patterns, feeding habits) and biological aspects is lacking. Thus, it is difficult to assess and quantify the importance of their ecological role and the consequences of anthropogenic impacts on their populations and the environment. However, given increasing evidence of the importance of large marine predators, it is reasonable to infer that substantial changes to the distribution and abundance of dolphins in the GBR could have strong consequences for the structure and functioning of coastal and open ocean ecosystems in the GBR. It is also important to note that some of the interactions or their follow-on consequences have only been shown because of substantial long-term research effort. Such effort has not yet been undertaken in the GBR, and perhaps may never be. The inability to demonstrate such effects should not be taken to imply that they have not, or will not occur. The precautionary principle should be applied here because of this lack of information.

Additionally, for many humans, dolphins have aesthetic value contributing to the beauty and diversity of the planet. This value has resulted in the proliferation of whale and dolphin ecotourism activities throughout the world. Tourism based on free-ranging dolphins, including boat-based tours, shore-based observation, swim interactions, and hand feeding, is one of the most popular icons for marine tourism along Australia's coastline and an increasing industry along the east coast of Queensland[11]. Although at present the level of wildlife tourism involving dolphins in the GBR waters is low, it is expected to increase. Thus, changes in dolphin communities occurring in the GBR could have substantial economic impacts on the tourism industry and local economies.

### *16.1.2.3 Significance of whales*

Most cetaceans apart from dolphins are referred to as whales. There are two main groups of whales: toothed (odontocetes), which includes the dolphins, and baleen (mysticetes). In the GBR, many species of odontocetes and at least seven species of mysticete have been recorded. Of the non-dolphin odontocetes, all species that have been recorded are deep diving whales including sperm and beaked whales. It is unlikely that these whales occur commonly in the GBR itself but rather inhabit adjacent deep waters. While the sperm whale is reasonably well known, the other species are not. Pygmy and dwarf sperm whales are found sporadically and are little studied. Even more cryptic, the beaked whales, a family comprising approximately one quarter of all species of cetaceans and second only to dolphins in marine mammal species diversity[58], are the least known group of large mammals in the world. These odontocetes are thought to all rely heavily on cephalopods as prey.

While four species of mysticetes are recorded with some regularity in the GBR, only the humpback whale is found routinely in large numbers in the area. Humpback whales migrate annually from summer feeding grounds in Antarctic waters to winter breeding grounds within the GBR[21,63,15]. The vanguard probably enters GBR waters in May with numbers increasing to a peak in August and then subsiding again with most gone by late October. During this time the whales calve, mate and fast[17,21].

Competition among males for access to females can be seen as energetic ‘competitive groups’ where a single female is generally pursued by several males[67,7]. Male humpbacks can also be heard producing complex acoustic displays known as ‘songs’[54]. While songs are likely to be associated with courtship and mating, the precise function is not clear, particularly whether it is aimed at attracting females or in dominance sorting or competition with other males[29,22,18,19].

East Australian humpback whales are currently thought to comprise a single discrete population with low levels of interchange with the west Australian and South Pacific populations[17,23]. This assumption has not been tested, however, and it is possible the whales may form more than one discrete population with core breeding areas in different parts of the GBR. The humpback population was hunted extensively by shore-based and Antarctic pelagic whalers in the 1950s and early 1960s and may have been reduced to less than one percent of its original level. Despite this, the population is recovering strongly with an estimated 7090 whales in 2004 and a rate of increase of between 10 and 11 percent per annum[52,53,46].

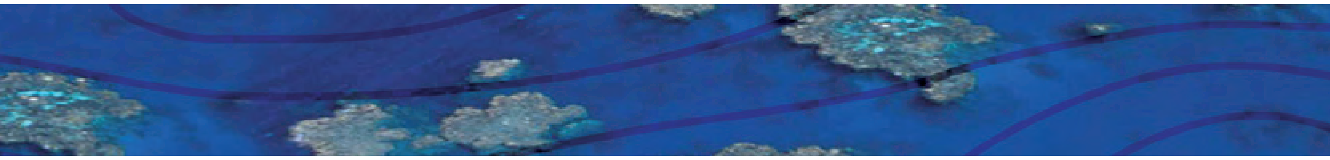
Humpback whales have the potential to form the basis of a thriving and important whale watching industry in the GBR in the future. As their population continues to grow strongly, opportunities for whale watching are increasing with steadily increasing densities of whales reported in many parts of the GBR.

The dwarf minke whale is probably one of two or three sub-species of the common or Northern minke whale[6,58]. While little is known about the habits of this sub-species, they form a well known winter aggregation in the Ribbon Reefs off Port Douglas and Lizard Island where they are the focus of a small but important whale watching and swim-with-the-whale tourist industry, the only one of its kind in Australia[12]. As with humpback whales, this aggregation probably represents the terminus of an annual migration with the whales likely moving to temperate waters for summer feeding.

Other mysticetes reported in the GBR include the fin, pygmy blue, sei and Bryde’s whales. Along with humpback and minke whales, these are all species from one of four extant mysticete families, the Balaenopteridae. Little is known, however, about the visitation of these less frequently seen species to GBR waters and it is likely that they occur sporadically, at low abundance or as occasional migrants to the area.

## 16.2 Vulnerability

In this section we first address the potential impacts of climate change common to each marine mammal group and then address those specific to each group separately. Throughout this volume a range of impacts have been addressed for varying taxa or attributes of the GBR ecosystem. Not all apply to marine mammals and thus for conciseness we have omitted those that do not apply. The absence of an impact in this section should be taken to indicate that we feel it will have little or no direct observable impact on marine mammals. For example, static organisms, such as seagrasses or corals will likely be directly affected by sea level rise while marine mammals are unlikely to experience any direct effect. Where indirect effects may be experienced these are addressed in the linkages section 16.3 (eg impacts on seagrasses due to sea level rise may have flow-on effects for dugongs).



### 16.2.1 Impact – ocean acidification

All marine mammals will be exposed to ocean acidification. However, there is presently no information with which to assess the sensitivity of marine mammals to the expected pH decrease. There have been a number of studies showing that fish populations can do relatively well in lakes with water at considerably lower pH than expected in the GBR, but the extent to which these can be extended to mammals is unknown. There is extensive literature on the effect that metabolic acidosis has on bone reabsorption in mammals[14,60], but this focuses on dietary or disease-based causes. We can find no literature on the effect of long-term immersion in fluids of lower pH. However, data presented on long-term ocean pH levels (Pandolfi and Greenstein chapter 22) indicates that the expected changes will not be outside the range experienced in the past by marine mammals. Consequently, we conclude that the risk of ocean acidification to marine mammals is relatively minor.

While there is unlikely to be a direct effect of acidification, were this to adversely affect the distribution of prey species, there may be some effect on marine mammals. Some groups of squid in particular are extremely sensitive to pH[55] and changes in squid abundance may have large impacts on some odontocetes, particularly sperm whales and beaked whales. While fish are probably less sensitive to hypercapnia[55] changes in abundance may also occur.

As many of the mysticetes that are found in the GBR feed in temperate and polar waters, acidification impacts on the Antarctic ecosystem in particular may also impact on GBR whales. Discussion of these impacts is beyond the scope of this book but may be widespread and serious.

### 16.2.2 Impact – sea surface temperature

In chapter 2, Lough described sea surface temperature of the GBR as greater than 29°C in the summer in the north to less than 22°C in winter in the south. Increases in mean sea surface temperature are predicted to be 1 to 3°C by 2100, but are likely to be greater in winter and greater in the south.

#### Dugongs

It seems unlikely that the range of dugongs within the GBR will be limited by water temperature. The distribution of dugongs is known to be limited by colder temperatures[3,57], but there is little evidence of warm water limitation. Dugongs have a wide tropical distribution and are found in the Arabian Gulf where sea surface temperatures reach 36°C. This exceeds the projected increases described above.

The more likely scenario for dugongs is that their range will extend southward. The current limit of significant and consistent populations is Moreton Bay. In recent years dugongs have been sighted as far south as Sydney and archeological studies show them to be present in Aboriginal middens from the region[2]. Waycott et al. (chapter 8) suggest that seagrass distribution may also shift south. If this occurs, dugongs may actually become permanent residents in areas south of their current range, rather than such animals being considered unusual vagrants. However, Allen et al.[2] noted that the total seagrass meadows in New South Wales (NSW) are less than those of Moreton Bay alone (which currently supports some 500 dugongs[16]. Consequently, it is unlikely that the numbers of dugong occupying habitats in NSW under climate change scenarios will ever be substantial relative to the total GBR population of some 14,000[38,39].

### Dolphins

There is some evidence that warming of ocean waters has led to distributional shifts and changes in social behaviour of dolphins. Increased water temperatures in northwest Scotland have resulted in a decline in occurrence of cold water species of dolphins, an increase in the occurrence of existing warm water species and the addition of new warm water species to the community[37]. The group size of bottlenose dolphins in the Moray Firth, Scotland, and killer whales (*Orcinus orca*) in Johnstone Strait, Canada, varied from year to year in relation to large-scale ocean climate variation and local indices of prey abundance[34].

Most of the dolphin species found in the GBR are cosmopolitan, occurring throughout tropical, subtropical and temperate waters of the world. The only exception is the Australian snubfin dolphin, which is endemic to the Australian and Papua New Guinean Region[9]. The predicted 1 to 3°C rise in mean sea surface temperature in the GBR by 2100 may cause range expansions of warm water species and contractions of those more typically found in cold temperate waters. However, it is difficult to predict species-specific responses without adequate knowledge of their distribution and seasonal patterns within the GBR.

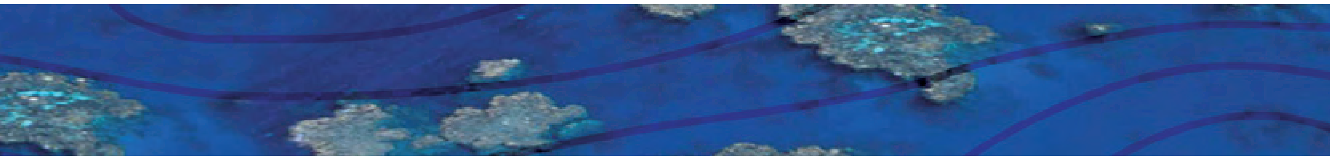
### Whales

The majority of baleen whales in the GBR are migratory species that routinely encounter large variability in water temperature. The exception is the Bryde's whale (or complex of whales)[61] which does not appear to be migratory, but which is found globally from tropical to temperate regions suggesting that it tolerates a range of water temperatures. It is unlikely that predicted changes in water temperature would have any effect on this group, as there is no evidence that this is a factor limiting or governing their current distribution.

Although probably more philopatric, the deep diving odontocetes are also routinely exposed to a large range in water temperatures with each dive. Sperm, pygmy and dwarf sperm whales are found in a wide range of latitudes[58] and their distribution is likely to be linked to primary productivity rather than water temperature. While some species of beaked whales are tropical and others temperate or polar[58], factors that control their distribution are not known but maybe related to diet and niche separation[36]. As they too experience a wide range of temperatures during deep dives, it is unlikely however, that water temperature alone is a major factor.

## 16.2.3 Impact – storms, floods and cyclones

Cyclones are expected to become more intense, but there is less certainty about whether their frequency or distribution will change (Lough chapter 2). Marine mammals may be vulnerable to storms, floods and cyclones via direct mortality caused by physical injury or via the effects of these impacts on food sources. The latter will be dealt with below in section 16.3. Their vulnerability to direct mortality will largely be a function of their distribution, particularly in relation to water depth and proximity to shore. Coastal dolphins and dugongs are likely to be most vulnerable, as they inhabit areas where it may be impossible to avoid physical disturbance via diving, and where stranding due to storm surge may occur. Offshore dolphins and whales are less likely to be injured due to the great water depths in which they are found.



### Dugongs

The vulnerability of dugongs to stranding during cyclones is likely dependent on a range of factors. The most well know example of such an event was that during Cyclone Kathy in the Gulf of Carpentaria in 1984[41]. The cyclone crossed the coast at high tide with the resultant storm surge carrying dugongs, turtles and other marine life over the shoreline and onto the flats behind. Stranded dugongs were found up to 9 kilometres inland. In total, 27 dugongs were seen, of which 23 were rescued, but Marsh et al.[41] considered it unlikely that all dugongs had been found. It should be noted that recent estimates suggest that the area supports several thousand dugongs[47].

While such examples are compelling, they are not common. Other cyclones have crossed the coast with few or no stranded animals reported. The increasing severity of cyclones may exacerbate this effect, but direct mortality is only likely where the cyclone crosses a high-density dugong population coincident with high tide. This alone is unlikely to be a significant threat to the GBR dugong population. However, the impact that cyclones and flooding may have on the food resources available to dugongs can be massive, and cause great disruption to local dugong populations. We address that issue in section 16.3.

A caveat on the above discussion is that there may be mortality effects that have gone unnoticed because of the difficulty in studying demographic processes in dugong populations. There are no data available on injuries or mortalities that may occur offshore as a result of cyclones.

Florida manatees are ecological correlates of dugongs, occupying similar habitats and feeding on seagrasses. They are also amenable to study, as they are very easily approached and observed and because the high occurrence of boat strikes in Florida means that individuals can be identified via the resultant scars. This has enabled the survivorship of manatees to be assessed over a period of nearly two decades and the effect of severe storms on survivorship to be estimated[32]. Over the period from 1980 to 1998 survivorship was essentially constant at 0.972 but dropped to as low as 0.817 in years with severe storms. Thus an increase in severe storms (such as cyclones) may pose a threat to dugong populations. However, Langtimm and Beck[32] were unable to identify the specific causes behind the reduced survivorship estimates and thus could not discern whether increased mortality was due to storm related injury, starvation due to lack of food or rather to permanent migration from the area.

### Dolphins

Increased frequency and intensity of cyclones in the GBR with climate change may have direct effects on coastal dolphins via stranding as a result of storm surge. This will particularly affect species restricted to coastal areas such as snubfin, Indo-Pacific humpback and bottlenose dolphins. As mentioned above for dugongs, direct mortality will only be likely in the event where a cyclone crosses high-density populations of these species coincident with high tide.

A more serious threat posed by an increased frequency in cyclones and associated rain and flooding is an increase in the transport of pathogens and agricultural and urban-sourced pollutants into coastal waters of the GBR. As top-level predators, dolphins concentrate contaminants through bioaccumulation. High concentrations of heavy metals and persistent organic compounds containing halogens have damaging effects on marine mammals[65,66]. Recent studies have shown that pathogen pollution may have considerable negative effects on populations of coastal marine mammals[30]. The carcasses of three humpback dolphins recovered in the Townsville region between 2000 and 2001 were infected with *Toxoplasma gondii*[13], a terrestrial parasite that can be fatal or have deleterious effects to the health of marine mammals (eg infection with *T. gondii* is one of the leading causes of mortality of southern sea otters along the California coast[30]). The introduction of this parasite to the coastal ecosystem appears to be linked to runoff of contaminated water with cat faeces or litter carrying oocysts of *T. gondii*[45]. Given the apparently small populations of snubfin and humpback dolphins in the GBR[50], an increase in the incidence of this pathogen is of serious concern.

Cyclones and flooding will also have an impact on prey availability to the dolphins. We address this issue in section 16.3.

### *Whales*

Most baleen whales are present in the GBR outside the cyclone season and so are less likely to be impacted. Odontocete whales in the GBR are usually found in deep water and so cyclones are unlikely to have serious effects on them as strandings are less likely than for coastal dolphins and dugong.

## 16.3 Linkages with other ecosystem components

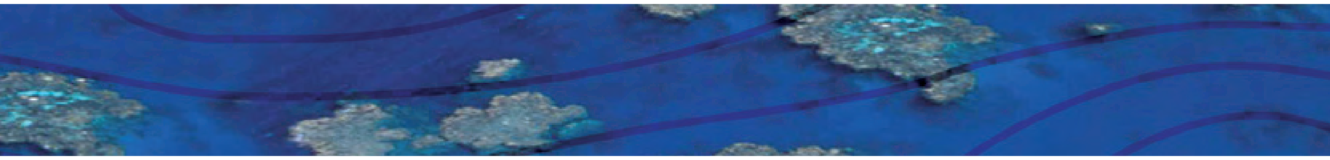
Marine mammals predominantly link to other ecosystem components via feeding. As large homeotherms, the energy requirements of marine mammals are disproportionately large and, where mammal densities are sufficiently high, they may exert significant structuring effects on prey species at both population and community levels. Consequently, this is the avenue by which climate change is most likely to exert an influence on marine mammals. Similarly, where marine mammals are affected by climate change or other factors, the broader consequences are likely to be seen most clearly in their food resources.

There are few commonalities between marine mammal groups in their food sources. Despite the distributional overlaps between dugongs and coastal dolphins their food sources are entirely different and thus we have assessed them as such.

### Dugongs

The most likely way for the effects of climate change to manifest on dugong populations will be via effects on seagrasses, the dugong's primary food resource. Waycott et al (chapter 8) described in detail the potential responses of seagrasses to climate change. Briefly, increasing temperatures may cause seagrass distribution to contract seaward, but rising sea levels may counter that effect to some degree. Flooding and sedimentation may also reduce seagrass density or availability. However, throughout the chapter, Waycott et al. note that pioneer species such as *Halophila* and *Halodule* are likely to be less affected than those adapted to more stable conditions. In fact, some more stable meadows may change species composition towards pioneer species.

This last point is important for dugongs, as they feed preferentially on pioneer species. If pioneer species of seagrass fare well under climate change scenarios then so too might dugongs. However, Waycott et al. caution that some intertidal and shallow subtidal seagrass meadows (which are important to many dugong populations) may become more prone to 'boom-bust' cycles, potentially threatening seagrass dependent species because of unpredictable loss of local resources.



It is important also to consider whether dugongs are currently limited by food resources. That is, if seagrass resources are diminished, will it impact significantly on dugongs? Above we described the work of Marsh et al.[43] who estimated the carrying capacity of the Queensland coast south of Cairns for dugongs and compared it to present population size. The conclusion was that the urban coast region could support approximately 30,000 dugongs. At the whole of GBR scale, unless seagrasses are reduced dramatically under climate change, it seems unlikely that the dugong population will be reduced. We caution, however, that this conclusion is based on regional scale interpretation. It remains possible that at the local scale individual dugong habitats might be disproportionately affected. This would depend on a suite of factors as addressed by Waycott et al. (chapter 8). At present, there are insufficient data to evaluate the possibilities at such a scale.

Despite the low level of concern for overall seagrass resources, there is one mechanism by which local dugong populations might be severely affected by climate change. Cyclones, and their associated flooding, can have a devastating effect on seagrass resources at the scale of an individual bay. The cyclone and two floods that hit Hervey Bay in 1992 caused the dugong population to crash from 2206 (+/- 402 standard error) to 600 (+/- 126 standard error)[56]. Many dugongs starved while others probably moved out of the area. The seagrass apparently recovered in six years[35], but it appears that it has taken until 2005 (over a decade) for the dugong population to recover[44]. Similarly, Heinsohn and Spain[27] noted an increase in catches of dugongs in shark nets after Cyclone Althea hit Townsville, which they attributed to increased movements in search of food. Stomach contents of those animals also showed a dramatic shift in diet, from seagrass to algae which was thought to be due to local seagrass resources having been destroyed[27]. If the intensity of cyclones becomes such that even greater losses of seagrass occur and/or the return time of cyclones becomes more frequent than the recovery time, then this may pose a significant threat to the dugong population of the GBR. Such an effect may be compounded by the subsequent stranding and other associated mortalities if cyclones make landfall at high tide.

### Dolphins

The distribution and abundance of dolphins is largely related to prey availability and predation risk[28]. Detailed information on the feeding habits of most species found in the GBR is lacking. Data from elsewhere indicates most dolphin species in the GBR are opportunistic-generalist feeders, eating a wide variety of coastal, estuarine and reef-associated fishes, cephalopods (mainly squid), and crustaceans both on the bottom and within the water column.

Munday et al. (chapter 12) indicate that changes in the physiology, distribution extent and abundance of fishes on the GBR due to rising temperatures is likely to be relatively small because: i) many of the fishes in the GBR have ranges that include predicted changes in sea temperature, and ii) phenotypic plasticity of resident populations, or gene flow from more northern populations will allow most GBR fishes to accommodate small increases in sea temperature. In the case of squid, and cephalopods in general, the situation appears to be the same: Squid and other cephalopods are ecological opportunists that can occupy broad trophic niches and respond quickly to environmental or ecosystem changes[59] Thus, in general, cephalopods have the intrinsic flexibility to adapt to climate change.

On the other hand, habitat degradation caused by increases in sea temperature, cyclone activity and sea level may have substantial consequences for the persistence of several species of fish. Munday et al (chapter 12) and Lovelock and Ellison (chapter 9) indicate that many species of fish in the GBR depend on corals and mangrove forests and are unable to persist once their habitat has been seriously degraded. Thus, significant declines in fish diversity and abundance may occur if there is large-scale loss of live coral and mangrove habitat resulting from climate change.

Declines in prey resources may result in shifts in the distribution and diet of dolphins[64,68], changes in their social structure[34], or local depletion/extinction[37]. The particular response of dolphins in the GBR will depend on their ability to adapt to changes in prey resources. Most species in the GBR are wide ranging and feed on a large variety of fishes and cephalopods. Thus most species are likely to be able to adapt to these changes. However, species such as the Australian snubfin and Indo-Pacific humpback dolphin, which are restricted to coastal estuarine waters and display high site fidelity, are potentially vulnerable to declines in prey resources[50].

### Whales

Baleen whales are thought to feed primarily in temperate or polar waters[8], migrating to the GBR or adjacent waters for their winter breeding seasons when they usually fast, and so are unaffected by the local availability of food resources. Changes in Antarctic and temperate ecosystems, however, including changes salinity, pH and current systems, may have profound impacts on these species by fundamentally altering these ecosystems[33]. The factors that trigger migration in baleen whales are not known. Whether or not changes in sea surface temperature or prey availability, particularly in the Antarctic, and resultant body condition alters the migratory timing of baleen whales remains to be seen.

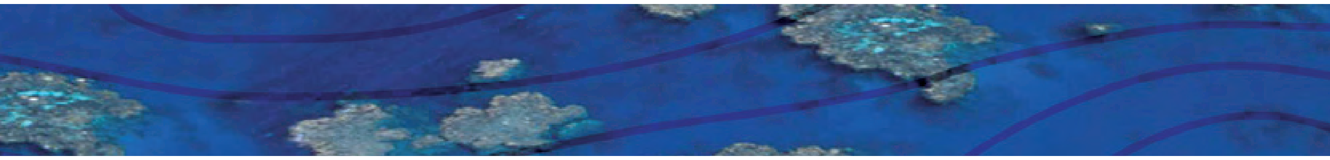
Beaked, sperm, pygmy sperm and dwarf sperm whales are all deep diving odontocetes that are likely to rely primarily on cephalopods and deep water fish. As mentioned above, changes to these prey groups may occur as a result of ocean acidification but the potential for this is not clear. It should be noted, however, that we are still far from having a complete picture of the distribution or ecology of any of these species in the GBR or adjacent waters, which makes definitive predictions even more difficult.

## 16.3.1 Constraints to adaptation

Marine mammal species have the advantages of mobility and the capacity to learn about their environment, both of which perhaps enhance their ability to adapt to changing circumstances. However, this suggestion should be qualified with observations of the current habitat choices of these species.

Dugongs utilise an inherently variable resource. Meadows of seagrass come and go over relatively short time frames and probably have done so over evolutionary time. Dugongs make frequent movements between seagrass habitats, sometimes covering distances of hundreds of kilometres[62]. At times they remain resident in these areas, but at others they return quickly to the point of origin, indicating that they are assessing alternatives. However, these movements are very individualistic and reflect different animals having differing knowledge of the distribution of alternative food sources.

The fact that some movements by dugongs bypass suitable alternative seagrass beds[62] and that many animals starved after the Hervey Bay floods described above, some having also passed by suitable habitats[56], indicate that if known resources are lost, individuals may not be effective at finding new sites. The persistence of dugongs in this environment shows that they do have the ability to adapt at a population level, but the question of the rate of change under climate change is again pertinent. At present there are insufficient data to assess whether this will be significant.



Coastal dolphins show quite specific habitat requirements. While there is some spatial separation between the two species, both Australian snub-fin dolphins and Indo-Pacific humpback dolphins show preferences for shallow water near river mouths[48,49,51]. These preferences are thought to be related to the productivity of the environments but it is not known whether, or how much, individuals would be able to alter with changes in overall productivity, or the distribution of productivity. Oceanic dolphins are wide ranging and feed on a large variety of fishes and cephalopods and thus are potentially more likely to adapt to changes in their environment. However, changes in their distribution and abundance within the GBR are likely to occur as a result of climate change. As for dugongs, preference for an inherently variable environment perhaps indicates a high level of adaptability, but whether the current or projected rates of environmental change will exceed adaptability is unable to be assessed with the current data.

### 16.3.2 Interactions between stressors

As noted above, there is limited prospect for any of the climate change impacts to directly affect marine mammals, given their mobility and general adaptability. Similarly, it is unlikely that such stressors will interact in any manner in which impacts on marine mammals can be reliably inferred. However, cumulative interactions can impact the food resources of marine mammals and these are addressed in the chapters on seagrass (chapter 8) and fish (chapter 12).

### 16.3.3 Threats to resilience

Climate change is only one of the many threats faced by marine mammals in the GBR. While assessment of the likely effects of climate change remains tentative, there are a number of other threats for which the evidence is more direct and more current. Some marine mammal species in the GBR are already under threat from incidental entanglement in gillnets and shark nets, pollution, overfishing of prey resources, and habitat degradation. Due to the lack of baseline data, or indeed current population estimates, for most species, the only species for which there are quantitative data to demonstrate a decline is the dugong. Marsh et al.[43] showed that catch rates of dugongs in the Queensland Shark Meshing Program declined by nearly 97 percent between 1962 and 1999. Given that: i) one of the identified causes of the decline was entanglement in gillnets[42], ii) gillnets are similar to shark nets, iii) shark nets are known to catch dolphins[26], and iv) coastal dolphins and dugongs show considerable overlap in distribution; there is a compelling argument that dolphin populations also are likely considerably reduced. Though whale and dolphin watching activities are in general low within the GBR, there is evidence that even low-level exposure to tour vessels can result in population declines over the long-term[10].

A large and stable population size is probably the most fundamental aspect of resilience to additional impacts. If several of the marine mammal species in the GBR have reduced population size, then there is the prospect that the cumulative effect of these threats and climate change may result in the loss of those species, particularly those restricted to certain types of habitats and those with small geographic ranges (eg Australian snubfin dolphin, Indo-Pacific humpback dolphins, dugongs).

## 16.4 Summary and recommendations

### 16.4.1 Major vulnerabilities

The major vulnerabilities of marine mammals under climate change are related to effects on their food resources. There is considerable uncertainty over what these will be, but they may include reduced quantity or quality and greater spatial and temporal variability, affecting the ability of marine mammals to adequately utilize the resource. These effects are exacerbated by the reduced population sizes of many marine species, particularly coastal species such as the Australian snubfin dolphin, Indo-Pacific humpback dolphin and the dugong.

### 16.4.2 Potential management responses

As described above, for dugongs and dolphins the principal effects of climate change are not likely to be from climate change itself, but rather the effect of climate change on food resources. The situation is similar for baleen whales, but the effects are likely to occur well outside the GBR. As the potential management responses to address impacts on these resources have been covered in detail in their respective chapters (seagrass: Waycott et al. chapter 8, fish: Munday et al. chapter 12) we do not do so here. We note specifically, and support, the suggestion in those chapters that terrestrial runoff needs to be controlled to maintain water quality. In addition to the benefits for seagrass and fish, this may confer direct benefits to dolphins and other marine mammals via the reduction in input of terrestrial toxins and pathogens.

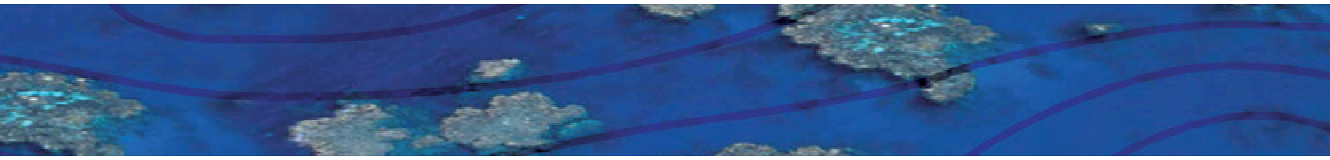
More generally, we support the oft-repeated view in this volume that if climate change impacts are difficult to control, then the appropriate precautionary action is to control other factors known to impact marine mammals and which are sensitive to management response. In the case of marine mammals, such impacts include net entanglement, boat strike, marine debris, tourism and Indigenous hunting. Reduction in these impacts will confer on marine mammal populations greater resilience to withstand potential negative consequences of climate change.

### 16.4.3 Further research

Key information required for marine mammals, particularly cetaceans, will be distribution, abundance and habitat use. Perhaps because of the substantial logistical obstacles to studying these species, this information is lacking for many. More effective identification of key habitat requirements will allow more appropriate assessment of the risks posed by climate change and other impacts.

Even for the relatively well-studied dugong there is still uncertainty about important aspects of their ecology. In particular, the relationship between long distance movements and local seagrass resources is only beginning to be understood. Thus, for all marine mammal species, research into their interactions with food resources will be important.

As noted above, there are other more immediate impacts affecting marine mammal species in the GBR. However, while the fact that the threat exists is often well known, the relative importance of each is less well known. Similarly, the specific nature of the impacts and methods by which to control them are also unclear. Thus, we would see higher priority attached to research and management of these threats to be an appropriate response to climate change.



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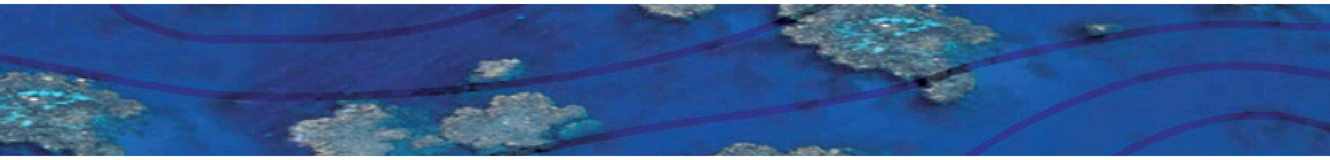

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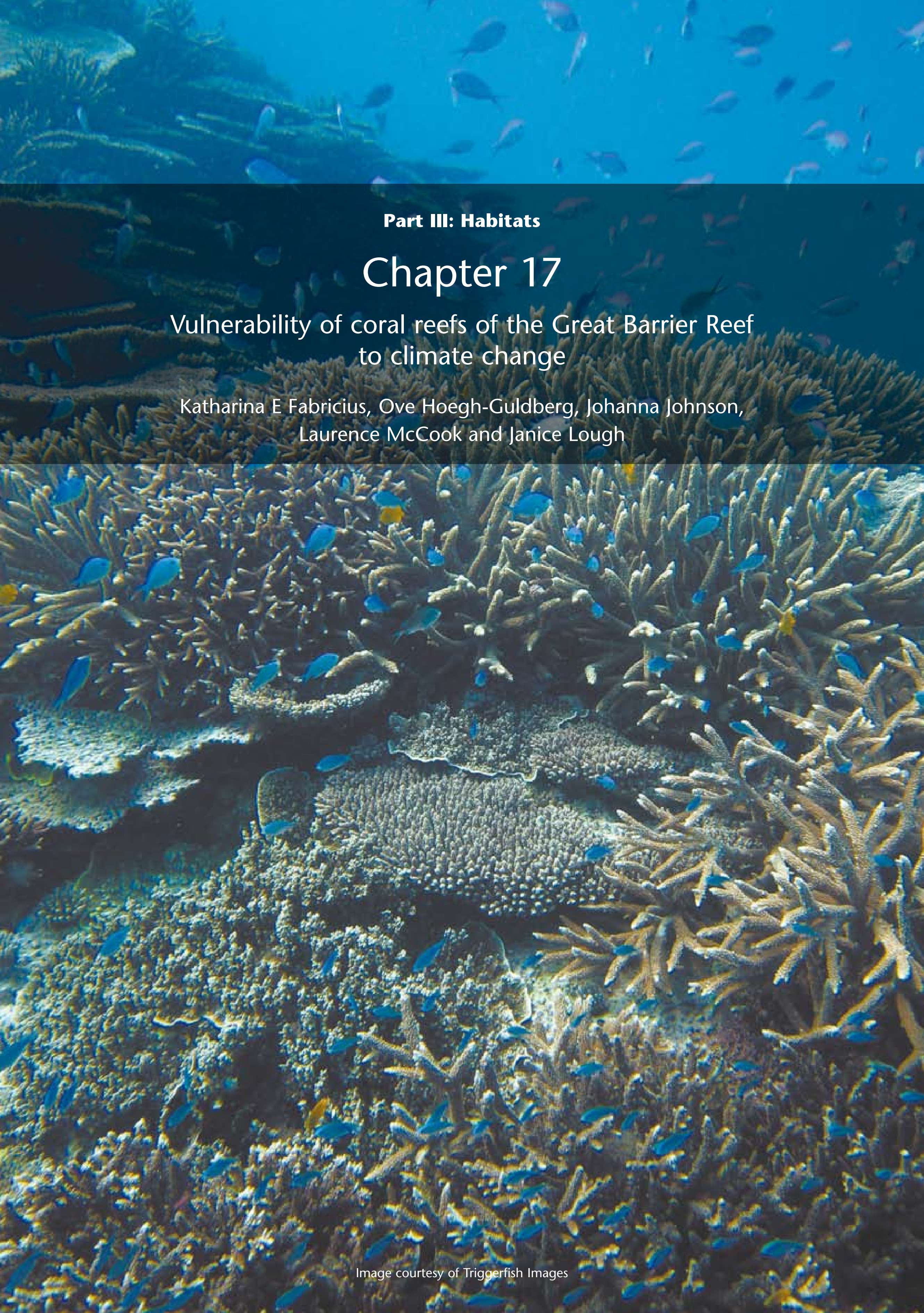

**Part III: Habitats**

# Chapter 17

## Vulnerability of coral reefs of the Great Barrier Reef to climate change

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Image courtesy of Triggerfish Images

## 17.1 Introduction

The Great Barrier Reef (GBR) contains the most extensive coral reef ecosystem on earth. It consists of 2900 coral reefs and 900 coral cays that cover approximately 20,000 $km^2$ of the total 345,000 $km^2$ area of the GBR Marine Park. As a consequence of unusually high summer sea surface temperatures, between 42 to 60 percent of the reefs of the GBR experienced mass coral bleaching in 1998[8]. Bleaching was also reported from 31 other nations around the world during 1997–1998. For example, about 50 percent of reefs in the Indian Ocean and south Asia lost much of their coral cover, and an estimated 16 percent of the world's area of coral reefs was severely damaged[43]. The event coincided with the strongest recorded El Niño-Southern Oscillation event (ENSO) and one of the warmest years on record[78,106]. In early 2002, another mass bleaching event occurred on the GBR, exceeding the 1998 event in scale and severity[8]. Again, it was linked to record summer sea surface temperatures, despite weak ENSO activity[8]. These bleaching events alerted the world to the vulnerability of coral reefs to climate change. The responses of reef-building scleractinian corals are now much better understood than those of other groups of reef associated organisms[12,54,25] (Hoegh-Guldberg et al. chapter 10). This chapter reviews what is known of the vulnerability of GBR coral reefs to climate change at the ecosystem level. We consider how the ecosystem is affected by: i) increasing sea temperature, ii) irradiance, iii) ocean acidification, iv) frequency of intense tropical storms and v) altered rainfall and river flood plumes. The chapter focuses on the ramifications of increased coral mortality on ecosystem functions, including rates of calcification and erosion, reduced structural complexity and thus provision of habitat and shelter for reef-associated species. The chapter also considers the implications of significant loss of coral cover resulting in shifts in trophic structure and competitive advantages for some species within the ecosystem.

Assessing the vulnerability of GBR coral reefs at an ecosystem level is complicated due to the natural complexity of the system. The GBR ecosystem has a range and diversity of habitat types represented by over 70 distinct reef and non-reef bioregions identified based on their contrasting geophysical and biological characteristics[35]. These bioregions represent a gradient from tropical to subtropical reefs (between 12 to 24 °S), and across the continental shelf from turbid and shallow coastal reefs to reefs in deep blue-water oceanic environments. Additionally, extensive submerged coral reefs, coral communities and coral-associated organisms occupy parts of the deep seafloor. The GBR has high biodiversity and complex interactions, which all contribute to a greater or lesser extent to shaping the ecosystem. The coral reefs of the GBR are formed by the calcium carbonate skeletons of over 400 species of hard corals, the carbonate deposits of a number of calcifying algae, foraminifera, molluscs, tube-forming annelid worms and octocorals, as well as abiotic carbonate precipitation. These complex carbonate structures form the habitat for many tens of thousands of species of protozoans, fungi, marine plants and animals. For example, more than 1000 species of marine plants, 1500 species of sponges, 4000 species of molluscs, 800 species of echinoderms and over 1500 species of fish have been recorded on the GBR to date, with new species being added every year. This high habitat and species diversity contributed to the listing of the GBR as a World Heritage Area in 1981. An assessment of the vulnerability of such a complex system, in which not all of the key processes are currently understood, will necessarily be simplistic and can only focus on a few of the processes and interactions that are presently better understood.

An assessment of the vulnerability of the GBR to climate change is important to better predict potential future changes and as a foundation to investigate and develop potential adaptation strategies. The contribution that all GBR industries (tourism, recreation and fisheries) make to the Australian economy has been estimated at A$6.9 billion (Australian dollars) per year[53,1]. Economic returns are generated from a highly profitable tourism industry, and smaller reef-related industry sectors such as commercial fisheries and recreational activities. Additional ecosystem services provided by reefs include coastal protection and the storage of libraries of bioactive substances being investigated for potential pharmaceutical benefit. The total annual economic value of coral reefs has been estimated at US$100,000 to 600,000 per square kilometre[115], although these values are probably underestimates as they only consider direct services and outputs. Due to their ecological and economic value, and amazing beauty, coral reefs are generally treated as the iconic habitat within the GBR.

## 17.2 Exposure and sensitivity to climate change and impacts on reefs

### 17.2.1 Sea surface temperature

#### *17.2.1.1 Exposure*

Sea temperature is a key factor for organisms associated with symbiotic dinoflagellates (zooxanthellae) or that have a narrow temperature tolerance range. Coral reefs grow in shallow areas with good light penetration where water temperature rarely declines below 18°C. Globally, coral reefs are, therefore largely restricted to tropical or subtropical waters (between 30 °N and 30 °S), and to coasts without regular upwelling of cool deep waters (as occurs along most western continental margins).

Tropical sea surface temperatures have risen in the past century by 0.5°C, which is largely attributable to increasing greenhouse gas concentrations in the atmosphere. This trend is expected to accelerate in the current century[59,60]. Regionally, patterns of exposure to such warming can be quite complex. Both long-term average baseline sea temperature and warming trends significantly differ along and across the GBR, and at local scales:

- The long-term mean annual sea temperature is 3°C higher in the far north than in the south of the GBR (Lough chapter 2).
- The mean increase in annual sea temperature to date has been greater in the south of the GBR (approximately 0.5°C warming at 24 °S) than in the far north (approximately 0.3°C warming at 12 °S).
- The difference between summer and winter sea temperature is greater in the southern GBR (6°C seasonal change) than in the far northern GBR (seasonal difference: 4°C due to the moderating effects of more frequent shading by clouds and warm winters in the north).
- The difference between summer and winter sea temperature is greater in shallower inshore waters of the GBR compared with offshore waters, as inshore sea temperature is more than 1°C warmer in summer and generally cooler in winter.
- At smaller scales, significant localised warming is often encountered in semi-enclosed bays and cooling from upwelling may occur in some offshore sections.

Major large-scale thermal stress events tend to coincide with periods that may include extremely low wind, low tidal amplitudes, low turbidity, high irradiance and clear skies[41,12], resulting in minimal wave-induced flow, minimal shading by clouds and reduced backscatter after particles settled. The build-up of such heating conditions is particularly critical during times when baseline temperatures are already high. Relief comes from wind or tidally induced currents that reduce thermo-stratification in the water, and break up the boundary layers over the benthos surface, or from clouds that reduce solar heating[109,85]. Light exacerbates the effect of temperature.

Organisms on a coral reef will experience even greater fluctuations in water temperature than the long-term averages suggest. For example, *in situ* observations at an Australian Institute of Marine Science (AIMS) automatic weather station[a] on Myrmidon Reef indicate a seasonal variation of average daily sea temperatures of about 5°C while differences between observed daily maximum and minimum sea temperatures are 9 to 10°C (Lough chapter 2). Marine organisms have adapted to their thermal environment to exist between the high and low extremes as much as the mean sea temperature. In addition to the direct influence of sea temperature, the thermal environment of some organisms may be influenced by the absorptive properties of their colony or body surfaces. While sea temperature is a good predictor for the former, the latter is affected by temperature as well as irradiance, water flow and surface colour. Colony surface temperatures in darkly pigmented corals, for example, can be greater than 1.5°C warmer than ambient water temperatures at high irradiance and low currents[31].

Episodically, organisms are exposed to summer sea temperatures that lead to physiological stress or even mortality if thermal tolerance limits are exceeded. For example, in 1998 and 2002 on the GBR, about 42 and 54 percent of reefs bleached respectively, and up to 5 percent were severely damaged in each event[b]. There was considerable heterogeneity in the extent of bleaching between reefs of the GBR. Such heterogeneity can be linked to climate, weather, spatial and oceanographic factors that contribute to determining local and regional temperature exposure. These factors, and measures to assess exposure, are summarised in Table 17.1.

#### *17.2.1.2 Sensitivity*

Coral reefs grow and survive in a narrow range of environmental conditions and are therefore particularly sensitive to small changes in sea temperature. The sensitivity of ecosystem properties such as calcification and productivity is inevitably derived from the sensitivity of species groups such as corals and plankton. Chapters 5 to 16 in this volume summarise what is known about the sensitivity of other taxonomic groups. A key message is that taxa associated with endosymbiotic algae have particularly narrow upper and lower temperature tolerance ranges, while other groups can survive at much higher temperatures (eg seven species of tropical seagrasses at 40 to 45°C for short periods[14]).

A diverse range of invertebrates is associated with endosymbiotic dinoflagellates, including many anthozoans (eg hard corals, anemones, zoanthids and octocorals), some sessile and pelagic hydrozoans (eg fire coral *Millepora* and some jelly fish), molluscs (eg the giant clam *Tridacna*,

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[a] http://www.aims.gov.au/pages/facilities/weather-stations/weather-index.html

[b] http://www.gbrmpa.gov.au/corp_site/info_services/science/climate_change

*Table 17.1* Factors that affect the exposure of coral reefs to sea surface temperature, reef sensitivity and potential impacts

| Exposure | Factors determining sensitivity | Potential and observed impacts |
|---|---|---|
| **Factors determining exposure:**<br>• Latitude<br>• Cross-shelf position<br>• Small-scale features (embayments, channels)<br>• Depth (thermal stratification in bays)<br>• Currents, waves, tides and wind facilitating mixing and gas exchange, preventing thermo-stratification and surface heating<br>• Upwelling of cool deep water bodies decreasing exposure<br>• Cloud cover<br>• Boundary layer conditions<br>**Measures to quantify exposure:**<br>• Mean summer sea temperature<br>• Long-term seasonal change in mean and maximum sea temperature<br>• Three-day maximum sea temperature<br>• Degree heating weeks (intensity and length of exposure)<br>• Turbidity<br>• Flow and other factors that determine heat flux | • Species-specific phenotypic plasticity in temperature tolerance<br>• Prior physiological stress (eg from low salinity, high nutrients)<br>• Mobility<br>• Association with endosymbiotic algae<br>• Exposure history (eg exposure to high light and temperature)<br>• Community composition | **Rise in mean annual water temperature:**<br>• Accelerated metabolism, enhanced primary production, calcification, growth up to a threshold; declining rates thereafter due to heat stress<br>• Lower water column productivity, less food for filter and plankton feeders, altered food webs and reef productivity<br>• Altered reproductive timing (eg desynchronisation of spawning, shifted breeding season)<br>• Range extension towards the south of heat sensitive species<br>• Shifts in relative abundances of temperature tolerant versus sensitive species<br>• More diseases<br>**Increased frequency and severity of extreme temperature events:**<br>• Damaged photosystems in primary producers<br>• Corals: bleaching and increased mortality; lower reproductive output, reduced cover, lower structural complexity, lower reef calcification<br>• Coral-associated organisms: less shelter and habitat due to low structural complexity<br>• Facultative coral symbionts or epibionts: local extinction of highly specialised species (eg coral-associated gobies)<br>• Fish: shifts in distribution, shifts in life history traits<br>• Macroalgae: higher abundances (more substratum available, less shelter for herbivorous fish)<br>• Internal bioerosion: more dead coral available as substratum for bioeroding organisms, resulting in reduced structural strength<br>• Overall: reduced reef biodiversity, shift from net calcification towards net erosion, dominance by macroalgae |

and some nudibranchs), and flatworms (Platyhelminthes). For these species, conditions become uninhabitable if temperatures drop below 16 to 18°C for more than a few weeks per year, or if they increase by 1 to 2°C above long-term maxima for days to weeks. The latter damages the photosystem II in the dinoflagellate, disrupting the symbiosis between endosymbiotic dinoflagellates and host, and causing the host to 'bleach'[119]. In corals, bleaching tends to occur when seasonal maximum sea temperatures at that location are exceeded by 4-degree heating weeks (equivalent to four week of exposure to temperatures 1°C above the long-term summer maxima; Hoegh-Guldberg et al. chapter 10). However, this threshold is a coarse average across species and locations, as bleaching sensitivity greatly varies between host taxa, and (to a lesser extent) between the genetic varieties of zooxanthellae they harbour[79,74] (Hoegh-Guldberg et al. chapter 10).

The sensitivity of species to sea temperature varies spatially and temporally. Temperature tolerance is higher in communities that have developed in naturally warm waters, such as the far northern GBR, the Persian Gulf or local areas such as poorly flushed bays, than communities of cooler regions[7,33]. For example, some corals with prior exposure to high temperature or high irradiance on intertidal reef flats regularly exposed to low tides and high temperature variability have also been found to be less sensitive to heat exposure, either through local selection or possibly through acclimation[13]. Similarly, whether the reproductive output of reef fishes is affected by increased sea temperature depends on whether they reside in locations close to their thermal tolerance limits for reproduction. Some species from predominantly temperate water fish families (eg *Pagrus auratus:* Sparidae) already appear to be at their thermal limit for reproduction in tropical water[105] and their populations on the GBR may decline as sea temperatures increase.

For most species groups and ecological processes on reefs, relative sensitivity to heat exposure and the mechanisms of temperature damage are still poorly understood. This is partly because of the high number of species that have not been studied, but also because field surveys of sensitivity are unavoidably biased by several factors. For example, the timing of surveys crucially influences results: a survey conducted soon after the onset of heat stress will result in high scores for sensitive coral species and low scores for more persistent species, whereas a survey conducted a few weeks later will show mostly persistent species in a stressed state, since the sensitive taxa will have already died and disintegrated[6]. Secondly, a community that has previously undergone a severe heat exposure will exhibit apparently low temperature sensitivity during the next heat exposure, if sensitive species have not yet re-established and the community consists of mostly persistent species.

### *17.2.1.3 Potential and observed impact*

#### Rise in mean annual sea temperature

Water temperature is one of the most important variables determining ecosystem function in the marine environment. External temperature controls metabolic rates, which, during non-stress conditions, increase with increasing temperatures in all but warm-blooded organisms. Consequently, persistent warmer temperatures can accelerate life history and population parameters such as growth and reproductive age, and ecosystem properties such as rates of calcification and community metabolism, until they reach a level where temperature stress accumulates and rates start to decline[75].

While warmer sea temperatures increase growth rates in some organisms such as fleshy macroalgae, they may slow down growth in others because of the relative lower nutrient concentrations in warmer compared to cooler water. At higher temperatures, water column productivity accelerates, depleting the standing stock of dissolved and particulate nutrients including phyto- and zooplankton (McKinnon et al. chapter 6). For example, kelp and other temperate brown macroalgae grow most prolifically at cooler temperatures where nutrient concentrations are higher than in warmer nutrient-depleted waters[18], while the productivity of other macroalgae might increase at higher temperatures (Diaz-Pulido et al. chapter 7). Similar responses are likely to occur in other species groups, exemplifying that shifts in the relative abundances of species are to be expected, with profound but yet poorly understood consequences for ecosystem properties and species interactions.

Altered reproductive timing has been linked to rising mean annual sea temperature. Of particular concern is a potential desynchronisation of the mass-spawning event of corals that occurs annually in the GBR. Thousands of coral species from unrelated taxa synchronise their annual spawning based on sea temperature and moon phase[5]. The role temperature plays is demonstrated at Magnetic Island off Townsville, where waters are approximately 1°C warmer than in the surrounding region and a proportion of species spawn one month earlier on this reef than conspecifics in cooler waters near-by. Similarly, reproduction of fishes on the GBR appears to be triggered by increasing sea temperature in at least some tropical reef fishes[16,17,98,49], including coral trout[102]. Increased temperature could cause an earlier start to the breeding season in these species, and possibly a longer breeding season if thermal limits for reproduction are not exceeded.

Increased sea temperature may also impact life history traits of some reef fish species. Based on variation in life history traits of some tropical reef fishes across temperature gradients we might expect increased sea temperature to generally shift life histories towards: i) smaller maximum size, ii) reduced maximum longevity, iii) earlier maturation iv) longer breeding seasons, and v) shorter larval planktonic durations hence shorter dispersal ranges. These shifts would be observed as long-term trends in mean values for populations at any given location.

Theoretically, coral reef communities of the GBR might be expected to shift to cooler locations further south as global ocean temperatures warm. However, latitudinal expansion in coral distribution would crucially depend on a simultaneous southerly expansion of high aragonite saturation with warming waters, which is unlikely as a temperature-related increase is predicted to be much smaller than the decline due to ocean acidification[44]. Furthermore, there is a decrease in shallow water areas and an increase in siliceous sediments further from the equator, creating conditions that are less suitable for reef development. Therefore, while increased temperature may improve conditions for corals and other tropical organisms in higher latitudes, and thereby extend the range of some reef species, climate change is not expected to result in a poleward shift of coral reef ecosystems.

### Increased frequency and severity of heat periods

Short-term impacts and predictions of the potential long-term impacts of an increasing frequency of heat episodes on GBR coral reefs are based on data collected during the two thermal events in 1998 and 2002, and on the present understanding of mechanisms involved in reef disturbance and recovery (Table 17.1). There are documented impacts of these events on many components of the ecosystem, including corals (Hoegh-Guldberg et al. chapter 10), seabirds and baitfish distribution

(Congdon et al. chapter 14, Kingsford and Welch chapter 18) and fleshy macroalgae (Diaz-Pulido et al. chapter 7). Changes to coral cover and available substrate following disturbance resulted in phase shifts on some reefs to an algal-dominated system.

The primary observed impact of episodic heat periods on coral reef is stress in photosynthetic organisms, coral bleaching and increased mortality of other temperature-sensitive species (chapters 5 to 16). Local diversity in reef communities is immediately reduced after heat episodes with the most sensitive species disappearing while more robust species persist or expand, such as the replacement of sensitive coral species by fleshy macroalgae that was observed after mass bleaching mortalities[55,29,79,76,122,42]. For example, most species of reef-inhabiting ascidians disappeared within two years following the 1998 ENSO event, while two bioeroding species increased significantly in numbers[64].

Further shifts in species composition result from reduced recruitment and growth rates in stressed but surviving taxa. For example, corals recovering from bleaching have up to 80 percent reduced reproductive output and growth for up to two years after the event[82,113]. During recovery, communities initially consist of sparse populations of young colonies. Depending on nutrient levels and herbivore abundances, macroalgae can proliferate and blanket space previously occupied by corals, further retarding coral recruitment and reef recovery through space occupation. Such a phase shift has been described in detail in the Caribbean, where extensive macroalgal abundances established after storms removed adult corals and overfishing and disease removed the main guilds of herbivores[41,57]. Some evidence for such phase shifts also exists for the Indo-Pacific[87].

The indirect effects of coral mortality on organism groups not directly killed by the heat episode, but dependent on the reef complex for shelter, are likely to be severe (Hutchings et al. chapter 11, Munday et al. chapter 12). The exposed skeletons of corals that die after bleaching are colonised almost immediately by benthic algae and other pioneer colonisers, and in a short period, start eroding, with three main consequences. First, coral reefs shift from a state of net calcification to erosion, less able to withstand exposure to storm waves. Second, coral recruitment is inhibited. Third, habitat is lost for the numerous invertebrates and reef fishes that are associated with corals[88,117]. For example, fish abundance and biodiversity can decline severely in parallel with declining coral cover[69]. In one case from Papua New Guinea, more than 75 percent of reef fish species declined in abundance after loss of coral cover post-bleaching, with half declining to less than 50 percent of original abundance, and importantly, several rare species became locally extinct[63]. Munday[84] also demonstrated the local (and possibly global) extinction of a specialist species of coral-inhabiting fish (goby). This study suggested that overall, habitat specialists are more likely to be prone to extinction than generalists, because of their dependence on specific habitat, and because of restricted population size and limited spatial distribution.

A major mechanism for declines in fish abundance appears to be the loss of living coral as recruitment sites for juvenile fish. Research by Jones et al.[63] suggests that marine reserves will not always be sufficient to protect fish populations if coral mortality is not prevented. Similarly, abundances and species richness in reef fish species declined after the loss of coral cover and structural complexity from coral bleaching[124]. In a study from the Seychelles, Wilson et al.[124] reported abundance in six species as 'critically low', and the local extinction of four species of fish appeared likely. Small fish species had the highest probability of decline, possibly due to their dependence on coral for food and shelter, increased competition over the remaining space, increased susceptibility to predation, and because many reef fish species require complex coral framework to recruit from the plankton.

Reef fish contribute to maintaining a wide range of ecological functions in coral reefs, and changes in their abundance can have long-term implications on ecological processes. For example, many zooplankton feeding and herbivorous fish depend on the reef framework for shelter. Zooplankton feeding fishes contribute to the capture of pelagic nutrients and pass them through excretion into benthic communities[46]. Herbivorous fish species play an essential role in controlling macroalgal abundances. Herbivores often increase in abundance following a loss of coral cover[124], presumably because more area becomes available for algal growth following coral bleaching, however, even these species ultimately decline as habitat structure is lost[103,38]. Therefore, the concern is that as the reef structure is lost, an ultimate decrease in abundance of herbivores will result in less control of proliferating algae and delayed recovery.

Other examples of cross-benefits are the excretions of damselfish, *Dascyllus marginatus*, which enhance growth and reproduction in their host coral *Stylophora pistillata*[73]. Crabs of the genus *Tetralina*, which inhabit the bleaching sensitive corals *Acropora* and *Pocillopora*, also protect their host against sedimentation[112]. Both *Tetralina* and *Dascyllus* only inhabit living corals, so their habitat is locally lost with the death of their host corals. However, for most coral-associated species that disappear when the host dies, functional roles are poorly understood and consequences of their disappearance cannot be predicted.

In conclusion, it appears inevitable that coral reef communities will change profoundly in response to rising mean annual sea temperature and episodic heat events. This change will involve a loss of biodiversity, declining ecosystem functions and services such as reef fishery yields, and a reduced aesthetic appeal for tourists. Based on present trajectories it appears almost certain that the GBR will experience a significant reduction in diversity, with sensitive species becoming rare or disappearing if no refuges exist. Some robust species that can tolerate or even benefit from higher temperatures will proliferate and gain competitive dominance over others. Overall, the potential and observed impacts of ongoing warming and episodic heat events is likely to be a substantial simplification of structural and ecological complexity, a shift from coral to algal dominance, accelerated erosion, reduced abundances or loss of temperature sensitive species, and the eventual extinction of coral-associated highly specialised species with restricted distributions and small population sizes.

## 17.2.2 Irradiance

### *17.2.2.1 Exposure*

Irradiance (both visible light and ultraviolet (UV) light) is a key environmental factor for coral reefs. Coral reefs need sufficient irradiance for photosynthesis, and are therefore restricted to the upper 50 metres depth in clear oceanic waters, and four metres in turbid inshore waters[128]. However, too high levels of irradiance during hot periods can cause permanent physiological and structural damage to photosynthetic symbiotic organisms through photoinhibition and other stress processes.

Irradiance varies naturally by two to three orders of magnitude in coral reefs, at scales ranging from centimetres to whole reefs[3]. The main factors determining variability are time, local shading, surface orientation, depth, water clarity, latitude and cloud cover (Table 17.2). Globally, mean annual irradiance is greatest in shallow and clear waters of arid equatorial regions where sun inclination is steep and cloud formation is rare. On the GBR, exposure is greatest in shallow clear offshore waters, decreasing with depth and towards the coast as suspended particles backscatter a large proportion of solar irradiance on turbid inshore reefs. Latitudinal differences in irradiance on the GBR involve sun inclination angle and cloud cover, both of which are greater in the northern than the southern GBR (Lough chapter 2).

Irradiance can be affected by climate change through two mechanisms. Firstly, climate change can alter weather patterns and hence cloud cover. Cloud cover is reduced during droughts, but can also increase due to greater evaporation from warm sea surfaces. Changing weather patterns may also alter the frequency of drought-breaking floods, leading to terrestrial runoff of sediments and nutrients into the oceans that can reduce water clarity at regional scales up to several weeks[4].

***Table 17.2*** *Factors that affect the exposure of coral reefs to changes in irradiance, and direct or proxy measures*

| Factors determining exposure | Factors determining sensitivity | Potential and observed impacts |
|---|---|---|
| • Water depth<br>• Turbidity<br>• Latitude (sun inclination)<br>• Cloud cover<br>• Surface roughness (waves)<br>• Steepness and aspect of reef slope<br>• Diurnal and seasonal changes | • Photosynthetic versus non-photosynthetic organisms<br>• Symbiotic versus non-symbiotic<br>• Pigments that absorb photosynthetic and UV radiation.<br>• Species-specific photoacclimation<br>• Susceptibility to, and factors that heighten photoinhibition and photodamage (eg anomalous temperatures)<br>• Orientation and depth of sessile organisms that can't move into shade | • Damage to photosystem, damage to DNA<br>• Increased mortality, reduced reproduction and growth<br>• Shift between phototrophy and mixotrophy/ heterotrophy<br>• Breakdown of symbiosis |

### *17.2.2.2 Sensitivity*

The photophysiology of corals, and their sensitivity to altered irradiance, is reviewed in detail in chapter 10 (Hoegh-Guldberg et al.). For most photosynthetic organisms on coral reefs, a moderate dose of irradiance, which reaches but not greatly exceeds saturation irradiance for several hours a day, should provide ideal conditions for growth. Extremely high levels of visible light and ultraviolet radiation can stress or permanently damage both photosynthetic and non-photosynthetic organisms, disrupting photosynthesis and damaging protein, DNA and symbiosis. While mobile organisms can move into shade to avoid damaging irradiance, sessile organisms that grow on upper surfaces in shallow water incorporate pigments such as mycosporine-like amino acids to protect against damage by ultraviolet radiation[26]. For photosynthetic organisms such as corals and benthic algae, extreme levels of photosynthetically active radiation can lead to photoinhibition and damage to

the photosynthetic apparatus, reducing productivity, growth and reproduction[36]. Too low irradiance doses can also cause stress, by impeding photosynthetic carbon acquisition and therefore growth and reproduction[4].

Within limits, corals can compensate for changes in exposure to light by photoacclimation, greatly widening the environmental niche where species can grow[2]. The sensitivity of corals to altered irradiance therefore greatly depends on their species-specific ability for photoacclimation. For species with poor photoacclimation, prolonged shading from thick cloud cover or turbidity can reduce primary production and growth rates as light for photosynthesis becomes limiting (Hoegh-Guldberg et al. chapter 10).

#### *17.2.2.3 Potential and observed impacts*

The entire GBR ecosystem is unlikely to be fundamentally altered by changing irradiance from climate change, as the fluctuation in irradiance is naturally high and no increasing UV trend has been observed. However, strongly reduced irradiance for a prolonged period of time, such as resulting from prolonged turbidity, can lead to mortality in photosynthetic organisms growing in deep water at the lower limit of their depth distribution[4]. Strongly enhanced irradiance for a prolonged period can also be fatal through initiation of DNA damage and of solar heat stress in very shallow and intertidal water. For example, local extinctions from heat exposure at intertidal sites in California can be predicted from the timing of low tides in summer, with low tides at noon leading to maximum solar heating[48].

The greatest impact of high irradiance is probably found during hot periods. This is because high photosynthetically active irradiance and ultraviolet radiation can exacerbate temperature-induced damage to symbiotic photosystems[62,54,71,72]. On the reef, large-scale thermal stress events, usually with periods of high irradiance and low winds[41,12,109], result in minimal waves, reduced shading by clouds, and reduced backscatter after particles settled. Such conditions lead not only to increased photophysiological stress, but also to a warming of the sea water and of benthos surfaces, with all processes potentially contributing to inducing coral bleaching and mortality[121]. Similarly, mortality from bleaching is often greatest in corals growing in shallow water and declines with depth. However, the reverse pattern is only found due to variation in community composition, with tolerant species being found in the shallows while more sensitive corals may be found in the deeper areas of a reef[55].

### 17.2.3 Ocean acidification

#### *17.2.3.1 Exposure*

Over the past 720,000 years atmospheric carbon dioxide ($CO_2$) concentrations have varied between 180 to 300 parts per million. Human activities have increased the atmospheric $CO_2$ concentration from 280 parts per million before the industrial revolution to 378 parts per million in 2005[106], with further increases up to 540 to 970 parts per million projected for 2100 if no drastic mitigation action occurs[59,47]. This increase in oceanic $CO_2$ has already resulted in a reduction of oceanic pH by an estimated 0.1 units[94,89] and of aragonite supersaturation from 4.6 to 4.0[65]. Depending on the $CO_2$ emission scenario used, further increases in $CO_2$ are expected to lower oceanic pH by 0.3 to 0.5 units over the next 100 years, and 0.3 to 1.4 units over the next 300 years[94]. As $CO_2$ increases and pH declines in the oceans, the ocean carbonate system also changes to lower aragonite supersaturation, possibly as low as 2.8 by the year 2100[65]. This has important implications for calcifying organisms such as corals, molluscs, coccolithophores and foraminifera that rely on carbonate supersaturation to form their carbonate skeletons (Table 17.3).

Coral records have shown that at Flinders Reef in the Coral Sea, oceanic pH has fluctuated with a periodicity of 55 years over the last 300 years, coinciding with the Pacific Decadal Oscillation[89]. However, the current and projected rate of $CO_2$ increase is about 100 times faster than has occurred over the past 720,000 years, that is, human greenhouse gas emissions are rapidly changing ocean chemistry to a level outside the range experienced by present-day coral reef habitats, and what most marine calcifying species have experienced throughout the past 55 million or possibly hundreds of million of years[97,94,47].

The distribution of excess $CO_2$ in the oceans has not been spatially uniform; carbonate supersaturation levels are highest in the tropics and decline to lower levels towards the temperate zone and areas of upwelling[97]. Aragonite saturation levels will however decline fastest in areas of highest supersaturation. The $CO_2$ related decline in supersaturation is far greater than the increases due to reduced solubility at warming temperatures.

***Table 17.3*** *Factors that affect the exposure of coral reefs to ocean acidification, and direct or proxy measures*

| Factors determining exposure | Factors determining sensitivity | Potential and observed impacts |
|---|---|---|
| • Atmospheric $CO_2$<br>• Latitude<br>• Temperature (small effect on solubility of key ion species) | • Calcium carbonate skeleton<br>• Rates of physical and biological erosion and dissolution | • Less biotic and abiotic calcification, shift from calcification to erosion<br>• Reduced linear extension ('growth') and skeletal density (stability) in calcifying organisms<br>• Increased primary production (some plankton species due to high availability of $CO_2$) |

### *17.2.3.2 Sensitivity*

Globally, coral reefs built of calcium carbonate can only be found in waters where carbonate ion concentrations are above 200 micromol per kg[65]. Evidence is strong that a reduction in pH following rising $CO_2$ will cause profound changes in the physiology of marine calcifying organisms and in reef processes. Direct effects will be greatest for calcifying algae such as crustose coralline algae and *Halimeda*, and calcifying invertebrates such as corals and foraminifera[94,51]. The sensitivities of calcifying and non-calcifying organisms to ocean acidification are described in detail in chapters 5 to 16.

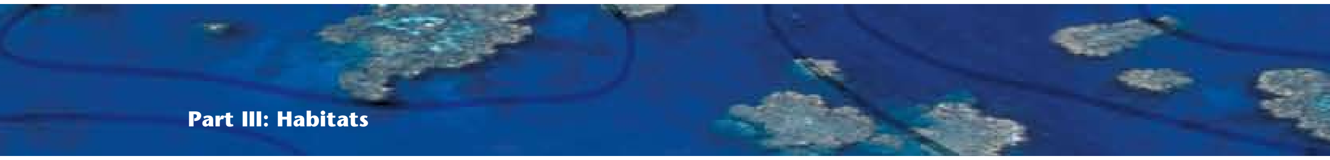
### 17.2.3.3 Potential and observed impacts

Some researchers have concluded that ultimately changes in ocean chemistry may have greater implications for many marine species than warming temperatures[47]. With atmospheric $CO_2$ rising, calcifying organisms of the GBR will be exposed to declining carbonate ion saturation state and seawater pH[94]. The full consequences of such dramatic and ongoing change in ocean chemistry are still unknown. Experiments have shown that a doubling of $CO_2$ partial pressure compared with pre-industrial $CO_2$ levels reduces calcification rates (the product of skeletal density and linear extension) in corals and coralline red algae by 10 to 40 percent[34]. A three-month experimental reduction in pH by 0.7 units was found to lower metabolic rates and growth in mussels[81] possibly from reduced rates of shell formation. An elevation of atmospheric $CO_2$ by 200 parts per million over six months, which lowered pH by 0.03 units, reduced both growth and survivorship in gastropods and sea urchins[108].

The physiology of non-calcifying organisms can also be modified by exposure to elevated $CO_2$ and reduced pH. However effects appear to vary substantially between groups, and limited studies exist in which $CO_2$ was realistically manipulated over longer periods, therefore longer-term effects and differences in sensitivity remain poorly understood. For example, short-term experimental $CO_2$ elevation resulted in reduced protein synthesis and ion exchange in some invertebrates, but not in the species of fish tested (reviewed in Pörtner and Langenbuch[91]). Importantly, non-calcifying marine plants are unlikely to be affected by increased $CO_2$, as most marine plants (except seagrasses) are considered carbon-saturated[39]. Little information exists on the effects of changing pH on fertilization and the survival and development of larvae and propagules, and other early life history stages in any one species.

Although fluctuations in oceanic pH, recorded at Flinders Reef throughout the last 300 years were unrelated to coral calcification rates, it is predicted that future changes in pH will be outside the range that coral reefs have experienced in modern times[89] and that ecosystem calcification will decrease while carbonate dissolution will increase[65,94]. Rising atmospheric $CO_2$ will therefore lead to dramatically reduced net calcium carbonate production compared with pre-industrial times, and severely weaken the ability of GBR coral reef habitats to support live coral and carbonate structures against the forces of physical and biological erosion and dissolution[67].

Presently, saturation levels are highest in the far northern GBR. By 2040, saturation levels are estimated to be 'marginal' throughout the GBR and by 2100 to be 'low' in the northern GBR and 'extremely low' in the southern GBR[67]. Aragonite saturation levels and pH will therefore drop below levels that are considered critical for calcification first in the southern GBR, preventing a latitudinal displacement of species towards cooler southern waters in response to ocean warming. These changes must be considered in conjunction with changes in sea temperature and other aspects such as the frequency and intensity of heat periods – the combined effects may well be greater than the sum of the parts. The flow-on effects of collapsed reef structures, when erosion exceeds calcification, on populations of fish and other coral-associated organisms that rely on the reef habitat are discussed in section 17.2.1.3.



## 17.2.4 Tropical storms

### *17.2.4.1 Exposure*

Coral reefs of the GBR are periodically exposed to highly destructive tropical cyclones during the summer monsoon season. The total amount of energy dissipation and monetary damage of structures above water increases as the cube of a storm's wind velocity (ie a doubling in maximum sustained wind speed results in an eight-fold increase in repair costs), with the diameter and transition time of the storm additionally contributing to determine its hazard[28]. Cyclonic winds can also damage structures under water, through energy dispersed by waves, swell and surges. This section will assess the direct damage to coral reefs from storm waves (Table 17.4). The following section will cover the indirect effects from cyclone-related exposure to floods and sediment runoff from land.

Spatially, tropical cyclone activity is highest between latitudes 16 to 20 °S, with activity declining to low levels south of 22° latitude, and extremely few occurring north of 12° latitude[92] (Lough chapter 2). Even so, almost all reefs of the GBR have been affected by at least one tropical cyclone within the last 30 years[92]. Exposure also differs across the continental shelf, around reefs and with depth.

***Table 17.4*** *Factors that affect the exposure of coral reefs to changes in storm frequency, and direct or proxy measures*

| Factors determining exposure | Factors determining sensitivity | Potential and observed impacts |
|---|---|---|
| • Latitude<br>• Cross-shelf position (exposure to open Pacific swell versus shelter behind outer reefs)<br>• Depth<br>• Reef aspect (windward versus leeward side) | • Mobility and territoriality in fish and invertebrates<br>• Growth forms – sessile organisms (encrusting or massive versus fragile or slender)<br>• Low aragonite saturation and high nutrient concentrations reducing skeletal density and substratum stability of corals<br>• Extent of bioerosion occurring in community<br>• Cross-shelf position (more fragile growth forms inshore)<br>• Coral community type | • Increased coral mortality, lower coral cover and diversity<br>• Removal and redistribution of accrued calcium carbonate structure<br>• Greatly reduced structural complexity (smaller colonies, fewer fragile growth forms)<br>• Increased availability of substratum for algae and other pioneers after destruction of living benthos<br>• Less shelter for coral-associated organisms<br>• Fewer coral dwelling fish and other organisms (reduced biodiversity)<br>• Shift in species composition towards taxa that are less affected by the outcomes of storms |

Windward sides on offshore reefs at the outer edge of the continental shelf are impacted by unabated swells from the open Pacific Ocean, while leeward sides on inshore reefs are the most sheltered locations. For example, outer reefs experienced 'phenomenal' wave heights (up to 15 metres), while waves on inshore reefs and along the coast were about five metres during Cyclone Ingrid in 2005 (predictions by the Bureau of Meteorology). As the depth of wave energy is a direct function of wave height, this cyclone damaged offshore reefs down to 20 metres and deeper, whereas damage on inshore reefs was restricted to less than five metres depth (K. Fabricius unpublished data).

Consensus appears to be emerging from predictive models that the intensity and maximum wind speeds of tropical cyclones is likely to increase with rising sea temperature, while the frequency of cyclones will remain unaltered[68,118,56]. The unprecedented number of severe hurricanes in the USA and the severity of three cyclones on the GBR in the summers of 2005 and 2006 have been attributed to unusually warm sea temperatures[28,120]. It is therefore possible that severe category 4 and 5 tropical cyclones may become more common on the GBR, further increasing the degree of disturbance of coral reefs.

### *17.2.4.2 Sensitivity*

Susceptibility to tropical cyclone damage varies widely between species and growth forms, and also changes across the continental shelf and with depth. In general, species with slim bases and slender branches, such as branching *Acropora* or large upright seaweeds (eg *Sargassum*), and organisms residing in shallow water are highly sensitive to cyclone damage. Whereas low growing (eg turf algae), massive or encrusting taxa (eg Porites corals) and deep water organisms have a higher survival probability[80]. Those made brittle by internal bioerosion will suffer even greater damage by storm erosion. On sheltered inshore reefs, branching corals tend to have lower skeletal density, more slender growth forms and more internal macro-bioeroders than their offshore counterparts that are adapted to frequent storm swells. Substratum on inshore reefs is also far weaker than on offshore reefs, due to low calcium carbonate precipitation and low abundance of crustose coralline algae (0.2% cover inshore, compared with greater than 35% on offshore reefs of the GBR[32]). Difference in substratum strength determines how susceptible massive corals are to wave damage, as massive colonies are dislodged rather than broken by waves[80]. Obviously, the combined effects of ocean acidification, nutrient enrichment from terrestrial runoff and storm damage on reef growth and complexity are likely to be far greater than the effects of each of these factors individually.

Populations of fishes, especially juvenile and sub-adult fishes, may also experience mortality and displacement, although some larger and non-territorial fish move into deeper water to avoid storm waves[70]. A large proportion of fishes and other mobile fauna later decline in abundances through the loss of habitat and shelter[124].

### *17.2.4.3 Potential and observed impact*

The main effects of storm waves on coral reefs have been categorized as: i) coral breakage, ii) coral colony dislodgement, iii) tearing of octocorals, iv) removal of reef matrix, v) burial of organisms by shifted sediments and rubble, vi) scarring of colonies by projectiles, vii) removal of algae on inshore reefs, and viii) algal blooms[22]. Reefs in the path of severe (slow-moving category 4 or 5) tropical cyclones can lose all but the most robust organisms down to more than 20 metres depth. Reef structure is flattened, and coral skeletons are often shifted into large piles or carpets of rubble, which are unsuitable as settlement substratum for new corals until consolidation. On offshore reefs, rubble is cemented together by calcium carbonate ($CaCO_3$) precipitation, and waves remove remaining loose pieces within a few years. On inshore reefs in contrast, rubble fields may remain unconsolidated for more than 10 years. Reef recovery from extreme category 4 and 5 cyclones is slow, because few colonies survive on site to serve as brood stock to recolonise denuded areas. Recovery times may be 20 years or more for severely damaged reefs, depending on connectivity to larval sources further upstream, and the survival rate of loose fragments. Occasionally, reefs that were stressed through other forms of disturbance (eg overfishing or poor water quality) have undergone a phase shift after being hit by a cyclone, developing a new and apparently stable state of algal dominance after corals had been removed by the storm[57,96].

Less extreme cyclones cause more patchy damage, with mosaics of damaged and unbroken patches side by side, and substratum complexity remaining relatively high. Such moderate damage sets back species that may otherwise start monopolising space, and hence may contribute to maintaining high diversity on coral reefs[90]. Unlike corals surviving temperature stress (with low reproductive output up to two years after the event), unbroken cyclone survivors produce a normal amount of gametes that will recolonise impacted areas in the following years unless there is no available substrate due to increased algal cover. The speed of recovery from tropical cyclones therefore depends crucially on cyclone intensity and its speed of passage, influencing the proportion of colonies that survive and the three-dimensional substratum complexity.

Populations of non-calcifying fleshy macroalgae such as *Sargassum* can also be reduced by cyclones if holdfasts are torn off the substratum[95]. Loosely attached ephemeral algae are easily removed, but their propagules may rapidly colonise the available space after coral mortality[27,124].

Disturbance by severe tropical cyclones, which reduces habitat complexity, has been found to immediately impact fishes from all trophic levels (but especially small fishes) more severely than disturbance by coral bleaching and by outbreaks of the coral-eating starfish *Acanthaster planci*, which kill corals but leave structural complexity intact. However, after skeletal erosion of dead coral colonies, the long-term consequences of coral loss through coral bleaching and crown-of-thorn starfish outbreaks may be much more substantial than the short-term effects currently documented.

As the total energy dissipation in storms increases as a cube of wind speed[28], a potential increase in the intensity of cyclones would have profound negative implications for coral reefs. Coral cover, substratum complexity and abundances of species that are slow colonisers would all decline. Fish stock and abundance of macro invertebrates that depend on corals would also decline, while algal cover would increase (see section 17.2.1.3).

## 17.2.5 Rainfall patterns and river flood plumes

### 17.2.5.1 Exposure

Nutrient concentrations are critical for healthy coral reefs, as most reefs are adjusted to growing in low-nutrient environments through efficient nutrient recycling within and between organisms. Changing weather patterns through climate change, with more frequent droughts and more

severe floods may significantly increase the amount of terrestrial runoff into the GBR, with profound ecological consequences.

Terrestrial runoff through river flood plumes discharges large amounts of nutrients, sediments and freshwater into the GBR lagoon. Due to the predominantly southeasterly winds and northward moving inshore currents, flood plumes tend to spread northward along the coast, constituting the most important source of new nutrients to the GBR lagoon[37]. The amount, characteristics and physical transport processes of this newly imported material vary spatially, depending on rainfall, soil and slope properties, and land use. Flood plumes regularly inundate some of the nearshore reefs, occasionally reaching some of the mid-shelf reefs but rarely reaching offshore reefs of the GBR[19]. Altered climate and rainfall regimes would, therefore, predominantly affect the exposure of some inshore reefs to freshwater, sediments and nutrients from terrestrial runoff, with the severity and frequency of exposure depending on their location relative to rivers (Table 17.5) and could increase the frequency of flood-born impacts on mid-shelf reefs.

Extreme flood events are either associated with low-pressure systems during the summer monsoon or tropical cyclones (see section 17.2.4). It is unclear from present model projections whether rainfall will, on average, increase or decrease in northeast Queensland with further climate change (Lough chapter 2). The magnitude of droughts and high intensity rainfall events are likely to be greater in a warmer world[106] compared to current climate conditions with consequent effects on river flow and

***Table 17.5*** *Factors that affect the exposure of coral reefs to changes in rainfall and river flood frequency, and direct or proxy measures*

| Exposure | Factors determining sensitivity | Potential and observed impacts |
|---|---|---|
| **Spatial factors:**<br>• Cross-shelf position<br>• Distance to river<br>• Wind direction and strength during plume<br>• Rainfall over the catchment (wet tropics versus dry tropics)<br>• Depth<br>• Reef morphology (gradual versus steep slopes, semi-enclosed bays versus well-flushed channels).<br>• Extent of drought conditions between rainfall and flood events<br>**Measures of exposure:**<br>• Salinity<br>• Sedimentation<br>• Nutrients<br>• Other pollutants (agrochemicals, etc) | • Species specific and life-stage specific tolerance of low salinity, low or variable light, high sedimentation, pollutants (recruits versus adults)<br>• Nutritional strategy (phototrophy versus heterotrophy, filter feeding internal bioeroders, planktonic larvae, etc)<br>• Nutrient limitation | • Increases in nutrients and sediments, leading to trophic shifts from phototrophy to heterotrophy; promotion of filter feeders, bioeroders<br>• Increased algal growth, reduced coral recruitment<br>• Increased flood mortality events.<br>• Reduced biodiversity, altered coral community composition<br>• More frequent outbreaks of crown-of-thorns starfish |

the spatial extent of flood plumes affecting the GBR. Southeast Queensland is predicted to become dryer, with fewer days of cloud cover and more frequent droughts, potentially affecting the runoff pattern in the southern GBR from the Burnett and Fitzroy Rivers. As in the northeast, most models predict more intense rainfall between long periods of drought. The interaction of these two factors is important as catchments that lose grass or tree cover during periods of drought (and more frequent bush fires) will deliver more soil, soil-associated nutrients and pesticides to the GBR during intense rainfall events.

### *17.2.5.2 Sensitivity*

The sensitivity of reef-inhabiting organisms to altered terrestrial runoff patterns, and the various components (sediments, dissolved inorganic nutrients, particulate organic matter, pesticides and light loss from turbidity) varies greatly between species, life stages, and functional groups. A review of the contrasting sensitivities of species and group is available[30] along with chapters 5 to 16 in this volume. Enrichment with dissolved inorganic nutrients and particulate organic matter, increased sedimentation and exposure to pesticides, cause a cascade of direct and indirect effects from which few ecosystem processes are spared. However, the groups most sensitive to these changes tend to be early life stages (eg coral recruits), nutrient limited phototrophs (eg some macroalgae), and nutrient-limited filter feeders (eg some internal bioeroders, some planktonic larvae). Nutrient enrichment promotes otherwise nutrient-limited groups, which then compete or prey upon other groups.

### *17.2.5.3 Potential and observed impacts*

Extreme rainfall, resulting in large river floods, brings low salinity, sediment and nutrient-enriched waters onto coral reefs. Freshwater plumes primarily affected nearshore reefs within 20 kilometres of the coast, with extreme events resulting in freshwater on mid-shelf reefs. Fabricius[30] reviews some of the main impacts of changing water quality on inshore coral reefs. The most serious effects of enhanced exposure to materials from terrestrial runoff are reduced rates of reproduction and growth in corals and improved conditions for internal macro-bioeroders and other heterotrophic organisms. Growth of some benthic turf and fleshy macroalgae can be promoted, leading to a shift in species composition on reefs from coral to algal dominance. In contrast, most crustose coralline algae are highly sensitive to sedimentation, and may disappear in areas exposed to terrestrial runoff, having implications for coral recruits that settle on them. More turbid waters, with less structural complexity, are also associated with lower abundances of herbivorous larger fishes, possibly also releasing macroalgal abundances on the GBR[126].

Lastly, drought-breaking floods have been associated with the initiation of primary outbreaks of the coral eating crown-of-thorns starfish, possibly because the planktonic larvae depend on high abundances of large phytoplankton for their development, and such phytoplankton is most abundant in nutrient-rich conditions[9,11]. Once primary starfish outbreaks have been initiated, outbreaks can spread to reefs far away from terrestrial runoff. Therefore, terrestrial runoff affects not only some inshore reefs but can also have severe effects on remote offshore reefs[11]. Overall, reefs frequently exposed to terrestrial runoff have a lower level of resilience (lower coral recruitment, more algae and greater internal bioerosion) compared to reefs not exposed to frequent runoff. This has important implications for reefs exposed to more frequent disturbance from climate-related changes such as coral bleaching and more intense storms.

## 17.3 Adaptive capacity

While there is considerable information regarding how coral communities may respond to the projected changes, little is known as to how coral reefs as habitats will adapt to these changes. It is important to understand that *adaptation* in this context is not the same as *biological adaptation*, which pertains to the influence of natural selection on the genotypes within a population (evolution). This is important as evolutionary processes take considerable time and are generally not fast enough to keep pace with the speed of changes envisaged under current climate projections. In this respect, *adaptation* entails processes such as physiological acclimation (phenotypic change) and shifts in community composition over time.

Chapter 10 (Hoegh-Guldberg et al.) reviews the extent to which coral communities are likely to adapt to climate change. These responses will occur over a range of different time scales and involve a degree of uncertainty in the direction and degree of adaptation possible. At the coral reef habitat level, adaptation will be expressed as a shift to hardier species, a shift toward certain functional groups or a phase shift to algal dominance. Disturbances will selectively eliminate sensitive species; more tolerant taxa will become dominant in the community so at the community-level there is a decrease in short-term sensitivity. This effect is location-dependent and will be difficult to quantify as little is known about the sensitivity of many species living on coral reefs. Understanding these shifts will also require greater knowledge of interdependencies. Work on fish populations is providing some important illustrations of how changes in one component (coral cover) can have major impacts on other components. Wilson et al.[124] reviewed and analysed studies that documented the effects of the loss of coral on coral reef fish communities at many sites across the globe. They found that 62 percent of fish species declined in abundance within three years of disturbances that resulted in a greater than 10 percent decline in coral cover. Abundances of species reliant on live coral for food and shelter were the most consistently affected, while some of the other species, such as those that fed on invertebrates, algae and/or detrital food sources actually increased in the short-term. These types of shifts in fish communities are assessed in chapter 12 (Munday et al.).

While global extinctions are unlikely in most species due to the size of distributions, local extinctions are probable as coral reefs decline. Some coral-dependent rare endemic species with small ranges however, could be at risk of global extinction, as specific reef features are critical to reproductive success (eg coral dwelling gobies[84]). These and other issues will need greater investigation before the extent to which the current rapid climate changes will drive extinctions in tropical marine ecosystems can be fully understood.

An eventual increase in the temperature tolerance of coral reef species through genetic adaptation is conceivable, but the time frame involved in such biological adaptation is most certainly too slow to keep up with the present and projected speed of climate change. Arguments supporting the concept of adaptation to higher temperatures are largely based on the spatial differences in temperature tolerances of reef species. For example, there is higher temperature tolerance in far northern GBR corals compared with southern corals, and in corals on intertidal reef flats that were previously exposed to bleaching-inducing levels of irradiance. In contrast, presently there is no mechanism known how calcifying organisms would adapt to low carbonate ion concentrations in the ocean. Throughout geological times, rates of calcium carbonate precipitation and biotic calcification have dramatically declined when carbonate concentrations or the carbonate saturation state in the oceans lowered due to enhanced volcanic activity. Coral reefs ceased to exist for many millions of years during and after such periods, and no means of adaptation seem to have been developed throughout the evolutionary history of corals and other calcifying organisms[65]. The predicted decline in carbonate ion concentrations to levels below 200 micromol per kg might represent an even greater threat to coral reefs in the medium to longer term than increases in sea temperature. This conclusion must be tempered with the observation that a 2°C rise in sea temperature over the next hundred years.

The loss of reef structure as atmospheric $CO_2$ concentrations approach 450 to 500 parts per million is a major constraint to adaptation. If the ability of reef calcifying organisms to deposit calcium carbonate dwindles to zero, then reef erosion will dominate, and species and communities that are dependent on the structural complexity of coral reefs will rapidly change. Reefs will be dominated by earlier successional stages of turf or macroalgae, lower coral cover, more robust species and lower diversity. In some sense, this would be an adaptive step as the ecosystem will be less disturbed at the same level of exposure, however it would represent a new and ecologically simpler community, and its splendor and value for activities such as fishing and tourism would certainly be dramatically lowered.

The adaptive capacity at the ecosystem level will mainly be limited to shifts in community structure. Given that the rate of climate change is perhaps two orders of magnitude faster than shifts seen after the last ice age, it is not expected that genetic evolution will keep pace with greenhouse forced climate change. The second highly important characteristic of global climate change is that the earth has moved away from a climate system that is stable over thousands of years to one which is changing rapidly at decadal time scales. The criteria for selection are, therefore, changing continuously, which makes it more difficult for ecosystems to adapt and presents major challenges for managing tropical marine ecosystems.

## 17.4 Vulnerability and thresholds

### 17.4.1 Future reef scenarios

A number of models have been developed to project future impacts of climate change on coral reefs, with projections ranging from shifts in coral community structure to total ecosystem collapse. Wooldridge et al.[127] modelled successional trajectories and how they are modified by climate disturbance regimes. Their models found that more heat-tolerant coral species such as massive *Porites* are differentially favoured over heat-sensitive species such as *Acropora*; however the prevention of macroalgal dominance in free space, by protection of herbivores and of water quality, determined whether or not there was a reasonable probability that viable hard coral populations would persist beyond 2050. The study clearly showed the essential role management actions can play in enhancing the resilience of reefs at a time of increasing disturbance frequency.

Johnson et al.[61] simulated the effects on reefs of bleaching events (like that in 1998) occurring once per decade on the GBR 200 years into the future. The model predicted significantly degraded reefs by 2100, with approximately 75 percent cover of turf and coralline algae and 25 percent coral cover with decadal bleaching but no further warming. With further warming at 0.1°C per decade the model predicted greater than 85 percent algae cover and less than 15 percent coral cover, while control reefs had 60 percent algal and 40 percent coral cover.

Such scenarios are relatively mild given that most projections suggest that bleaching events of the scale of 1998 will be annual events by 2050[50,107,24]. Using the lower range of scenarios, these studies indicate that communities and reef on the GBR will trend rapidly toward an algal-dominated state, resembling those in large parts of the Caribbean and Persian Gulf where benthic communities are now dominated by organisms other than corals[57,93]. The changes that will occur in the number and community composition of other reef organisms are less easily defined but are likely to be equally dramatic, due to the high dependency on healthy coral cover. The possibility of rapid evolution of thermal tolerance in reef species is unlikely and would have to match the rate of current and future climate change to maintain the current *status quo* (0.2 to 0.6°C per decade)[24].

These scenarios are also best-case scenarios given that they do not incorporate the interactive effects of other changes such as tropical cyclone intensity, sediment destabilization by drought, larger flood events and other factors, and because they do not consider adequately how ocean warming, acidification and sea level rise may interact. Currently, work that has explored how temperature and acidification interact is sparse and conclusions are surrounded by controversy (McNeil et al.[77] versus Kleypas et al.[66]). Understanding these interactions should be a priority. It is also clear that a better understanding of the implications of an increasing frequency of disturbance events like cyclones is needed. Since extreme events are rare, observational data are sparse to ground-truth models and they are more difficult to predict (and for organisms, more difficult to adapt to) than steady continual warming or less severe events.

### 17.4.2 Factors influencing resilience

The term *resilience* has been used widely to describe the overall ability of tropical marine ecosystems to recover from disturbances[99,23,121,58,86]. Resilience is critical for reefs to withstand the shifting and increasingly hostile conditions of tropical waters under climate change, and an essential factor in the assessment of vulnerability.

The resilience of reefs is inextricably linked to factors that influence the growth, reproduction and survival of key functional groups on coral reefs. The assumption is that well-connected reef systems generally take 10 to 20 years to fully re-establish after a massive disturbance. For example, in the southern GBR, in a region of high connectivity with undisturbed reefs, a storm reduced coral cover from 80 to 10 percent, with consequent decline in abundances of 88 percent of fish species investigated. Both coral cover and fish abundance recovered to pre-disturbance levels within 10 years[45].

Recovery is significantly slower on more isolated atolls that are poorly connected to larval pools. Studies of reefs in northern waters of Western Australia have shown that isolated reef systems recovered more slowly after the 1998 mass coral bleaching disturbance, than mosaic reef systems[111]. Similarly, live coral was reduced by 90 percent on the inner islands of the isolated Seychelles, with no apparent depth refuge[107]. Seven years later, fleshy macroalgal cover had increased seven-fold, dominating many of the carbonate reefs. Only one percent of the benthos consisted of habitat-forming branching and plate corals, while the remaining 6.5 percent of live corals were massive and encrusting growth forms that offered limited shelter for reef-associated organisms[124]. The finding of slow coral recovery, high macroalgal abundance and low abundance of grazing herbivores raises serious doubt about the potential of remote and isolated reef systems to recover, due to their poor connectivity to larval pools, despite few other human-induced stressors[124].

Even in well-connected reef systems, longer-term trajectories for the composition of reef communities is shaped by disturbance history, as the effects of cumulative disturbances are often greater than the sum of individual disturbances[57]. Offshore reefs in the northern GBR have experienced a series of serious large-scale disturbances within the last 15 years (bleaching in 1998 and 2002, severe *A. planci* outbreaks in 1988 to 1992, and 1995 to 1998, and category 5 Cyclone Larry in 2005[114]. Such repeated large-scale disturbances destroy brood stock and physical structure of the ecosystem at regional scales, severely compromising the ability of this region to recover from climate related disturbances in the coming decades.

More chronic disturbance such as fishing pressure and changes to water quality also greatly affect the resilience of reefs. For example, the over-exploitation of fish populations that are threatened by a loss of primary habitat due to climate change will clearly hasten the loss of these fishes from coral reefs. If fish populations on coral reefs are fished too heavily, then the functions they provide (grazing, predation) will dwindle with the effect that reefs may become vulnerable to a community shift away from coral and toward macroalgal assemblages. Lessons from other coral reef areas (eg Caribbean[57]) have demonstrated the importance of complexity and diversity in maintaining the ability of coral reefs to bounce back from disturbance. The key interactions are likely to be between climate change and more local human activities, such as fishing pressure, water quality and coastal land use. These elements are critical to societal responses to a rapidly changing climate. Given that projections indicate that disturbances are likely to increase in frequency and intensity under even low range emission scenarios, the importance of resilience over the coming decades will only increase. While there must be rapid action on the core issue of reducing greenhouse gas emissions, managing coral reef habitats to increase their resilience to change is vital if we are to give them the best change of surviving rapid climate change.

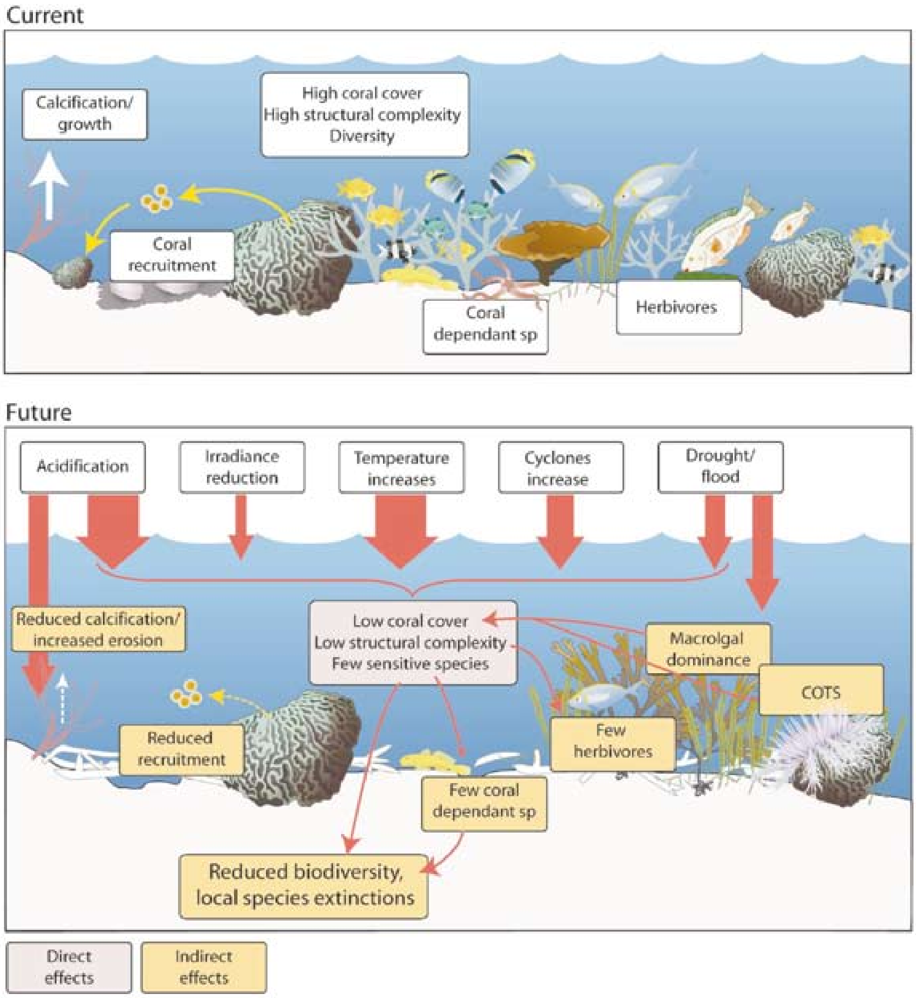
### 17.4.3 Vulnerability of coral reefs to climate change

Data compiled in the previous sections on the exposure, sensitivity, impacts, adaptive capacity and resilience of coral reef habitats confirm the findings from many previous studies. That the presently observed extent and rate of climate change, and the associated higher frequencies of extreme weather events, constitute a severe threat to the presence and future health of coral reefs[40,12,23,50,65,21,58,107,52]. Here we summarise in a simple conceptual diagram the expected responses of coral reefs to the five main climate change factors; temperature, irradiance, acidification, storms and floods (Figure 17.1). The diagram emphasises that some of the direct effects on reefs are common across the five main climate change variables: they all reduce coral cover, structural complexity and available habitat, and the number of sensitive species. The effects of acidification and temperature are of most concern, whereas changing irradiance is probably of least concern. These direct effects lead to flow-on effects on major ecosystem properties, including:

- Shift in balance from net calcification to net erosion.
- More bare substratum available for algae to settle, resulting in a shift from coral to algal dominance and presence of algae retarding coral recovery.
- Lower structural complexity leading to reduced habitat and shelter for fish and other coral-associated organisms.

- Local extinctions of sensitive, rare and highly specialised species; possibly some global extinctions of endemic species that are unable to migrate or compete with other species for resources.
- Reduced population sizes leading to reduced reproduction and recruitment, and longer recovery times.
- Simpler, ecologically less complex ecosystems, overall reduction in biodiversity.

***Figure 17.1*** *Predicted direct and indirect impacts of the five main climate change variables on coral reefs and how this will influence coral reefs in the future*[c]



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c Through repeated and prolonged impacts, reef communities will adapt to a state of lower sensitivity, however essential ecosystem properties such as biodiversity, reef calcification and coral dominance are lost

Additionally, each climate variable exerts certain specific direct and indirect effects on the ecosystem. For example:

- Ocean acidification reduces precipitation and enhances dissolution of carbonate.
- More frequent drought-breaking floods cause eutrophication, fostering the growth of macroalgae, filter feeders and outbreaks of coral-eating crown-of-thorns starfish.
- Higher temperatures accelerate growth in some organisms, however coral cover is reduced as bleaching thresholds are exceeded more frequently.
- Elevated sea temperatures reduce fecundity and recruitment in surviving corals.
- Warming leads to expanding or contracting geographic distributions of species that are adapted to specific temperature ranges, with unpredictable effects on species interactions.

### 17.4.4 Thresholds

Given the dependency of coral reef habitats on healthy coral populations, thresholds associated with change at the ecosystem level are inevitably similar to those of corals. In this regard, increases in sea temperature of more than 1°C will drive an increase in frequency and intensity of mass coral bleaching events, if no adaptation or acclimation occurs. Increasing concentrations of $CO_2$ will lead to a decline in pH and in carbonate ion to concentrations below 200 micromol per kg, a point at which corals will no longer calcify. As discussed above, numerous other changes will occur that will tip the balance of coral reef accretion and structure toward that typical of non-carbonate reef ecosystems. Based on this reasoning, the threshold for significant change to occur will be reached near 450 to 500 parts per million atmospheric $CO_2$ concentration. At this level, tropical seas will be further warmed by 1 to 2°C towards a temperature where coral mortality from bleaching will be a common event, and seawater carbonate saturation will be decreased to below 200 micromol per kg where calcification is severely reduced.

### 17.4.5 Assessment of spatial patterns of vulnerability to climate change

In order to identify regions in the GBR that are potentially most vulnerable to the effects of climate change, we qualitatively assessed the spatial distribution of all major potential environmental and biological predictors of vulnerability. West and Salm[121] and Salm et al.[101] identified the main physical and biological factors that contribute to bleaching outcomes, including the physical factors related to high temperature exposure, water movement, mixing and irradiance, and biological factors such as bleaching history, pre-exposure to low tides and high fish abundances as maintained through a network of protected areas. Done et al.[21] tested four of these physical and biological factors related to bleaching resistance in the GBR, using surveys late in the 2002 bleaching event. They found strong support for the effects of local warming, cooling by hydrodynamic mixing (modifying exposure and sensitivity), and sensitivity differing between four coral community types. They also found inconsistent effects of pre-exposure and relatively weak support for the role of irradiance in determining bleaching and mortality. Hoegh-Guldberg[50] concluded that the GBR will be more vulnerable in the south than in the north, due to greater sea surface temperature increases in the south (approximately 0.5°C versus approximately 0.3°C since the late 19th century, respectively; Lough chapter 2).

Berkelmans et al.[8] found that the spatial distribution of coral bleaching in the GBR in 1998 and 2002 was best explained by short-term thermal exposure (the 3-day maximum temperature around a reef) rather than longer-term median or deviations from the long-term average physical conditions. Wooldridge et al.[127] demonstrated the importance of water quality and herbivores in determining macroalgal abundance and hence the vulnerability and resilience of reefs. Skirving et al.[110] confirmed through mathematical models the important roles of low wind and currents and cloudless skies in inducing bleaching conditions. Many other studies have tested additional aspects of the potential contributions of physical and biological factors in enhancing or ameliorating hazard, and justifying their inclusion as risk factors. As a first and preliminary approach, a qualitative assessment of the distribution patterns in the spatial distribution of the potential risk and resilience factors across the GBR regions is compiled in Table 17.4 and in Figures 17.2 and 17.3.

Table 17.4a lists all of the known risk factors that may lead to an increased probability of climate impacts. Highest long-term means mostly appear to be located in the southern and central GBR, while none of the risk factors had highest values in the far northern and northern regions. For example, in the southern GBR alkalinity saturation and coral growth rates are assumed to be lowest while mean annual temperature variation and long-term warming trends are highest. Some of the risk factors are also assumed to have higher values in the inshore region compared with the offshore region, for example, long-term summer temperature averages are generally greater than 1°C warmer inshore than offshore (Lough chapter 2). Seasonal water temperature fluctuations are higher inshore due to longer water residency times on the continental shelf and distance from cool-water upwelling[125,8]. Corals on inshore reefs are also exposed to more variable irradiance from turbidity, and less swell-induced flow. They are also significantly darker than their conspecifics in cleaner offshore waters, in response to elevated particulate nutrients, nitrate and shading. All these factors may contribute to greater exposure to climate change, suggesting a potentially greater risk for inshore areas compared with offshore areas, and for the southern region compared with the far northern region of the GBR.

Table 17.4b lists the factors that are likely to contribute to reef resilience. It confirms the patterns seen in Table 17.4a of greater pressure in the southern region than in the far northern region. Again, many of the resilience factors have highest values around offshore reefs compared to inshore reefs (eg maximum cooling through upwelling and mixing from currents and swell offshore, and steeper slopes offshore than inshore).

This assessment, graphically summarised in Figures 17.2 and 17.3, suggests that at a regional scale, the far northern region, and in particular its offshore reefs, may have the most favorable spatial, biological and physical conditions within the GBR, supporting their relative greater resilience to climate change. In contrast, inshore reefs of the southern and central regions of the GBR appear to have the least favorable environmental conditions, exposing them to the greatest probability of long-term damage from climate change. However, it is very important to stress that the spatial pattern proposed here is preliminary, purely qualitative and conceptual. It will need to be rigorously tested using quantitative information and a formal risk mapping approach, to test and verify the apparent spatial patterns in the vulnerability of the main GBR regions to climate change. The relevance and relative importance of the different factors in protecting coral reefs will vary considerably spatially and temporally.

***Table 17.4*** *(a) Risk factors: regional conditions that increase vulnerability to climate change impacts on coral reefs in the GBR*[d,e] *(b) Resilience factors: regional conditions that reduce the vulnerability to climate change impacts on coral reefs in the GBR*

| 17.4a | Inshore | Offshore |
|---|---|---|
| **Far Northern** | Fluctuations in water clarity<br>Macroalgal dominance after coral loss | |
| **Northern** | Moderate fishing effort<br>Frequent crown-of-thorns starfish outbreaks<br>Macroalgal dominance after coral loss<br>Fluctuations in water clarity | Moderate fishing effort<br>Frequent crown-of-thorns starfish outbreaks |
| **Central** | High cyclone frequency<br>High sea temperature warming (approximately 0.4°C since 1903)<br>Most frequent crown-of-thorns starfish outbreaks<br>High fishing effort<br>Macroalgal dominance after coral loss<br>High exposure to terrestrial runoff<br>Fluctuations in water clarity<br>Reduced species richness | High cyclone frequency<br>High sea temperature warming (approximately 0.4°C since 1903)<br>Most frequent crown-of-thorns starfish outbreaks<br>High fishing effort |
| **Southern** | High seasonal temperature amplitude<br>High sea temperature warming (approximately 0.5°C since 1903)<br>Low alkalinity super-saturation<br>Low cloud cover<br>Low calcification<br>Moderate fishing effort<br>Macroalgal dominance after coral loss<br>Low species richness<br>Fluctuations in water clarity (drying catchments, episodic storms that increase sediment transport) | High sea temperature warming (approximately 0.5 °C since 1903)<br>Low alkalinity super-saturation<br>Low cloud cover<br>Low calcification<br>High fishing effort<br>Frequent crown-of-thorns starfish outbreaks<br>Low species richness |

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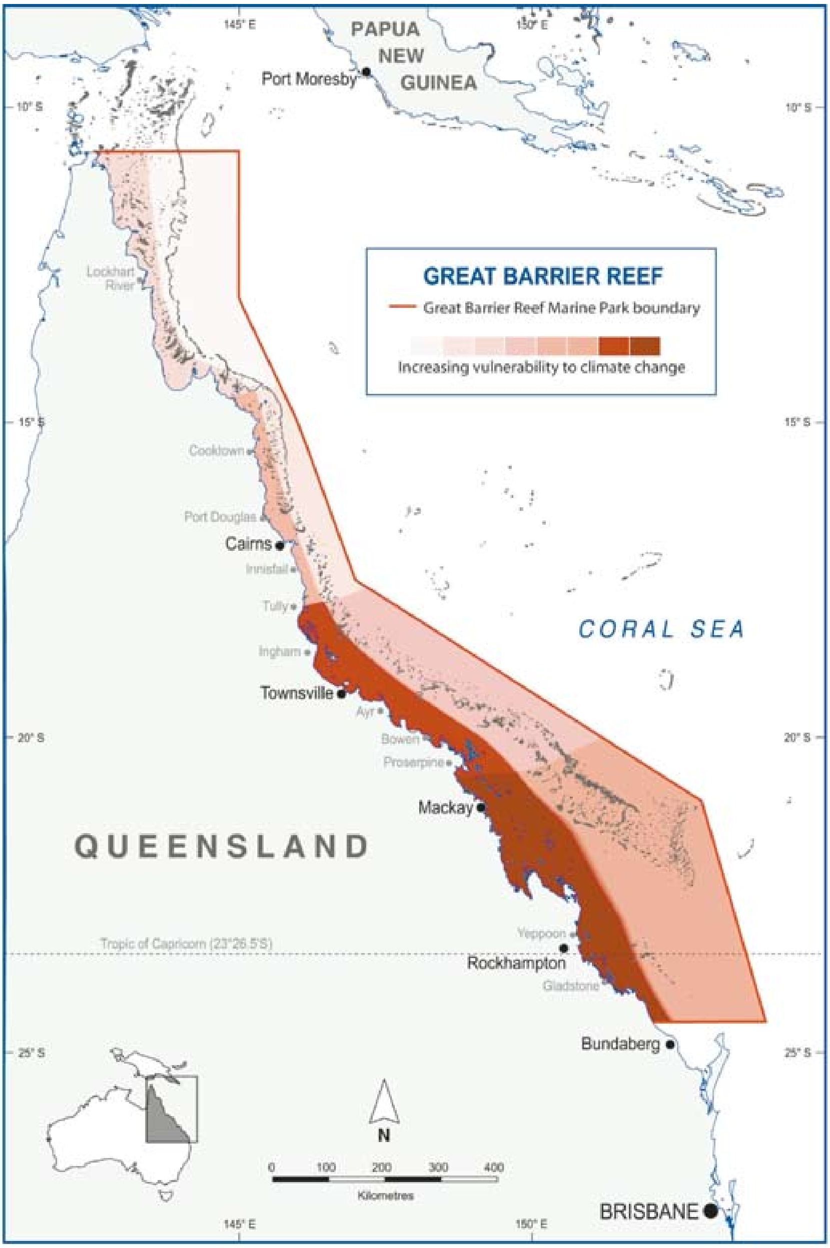
[d] The separation is based on the four GBRMPA Management regions: far northern (north of Lizard Island): 11.3° to 14.5 °S; northern (Innisfail / Mourilyan Harbour up to Lizard): 14.5° to 17.5 °S; central (north of Mackay up to Innisfail): 17.5° to 21.0 °S; and southern (south of Mackay): 21° to 24.5 °S. 'Inshore' represents the region reaching from the coast to 33 percent across the continental shelf (approximately to the outer edge of the lagoon), and 'offshore' represents from 33 percent across to the outer edge of the continental shelf where oceanic processes dominate.

[e] Fishing effort estimates are based on the Queensland Department of Primary Industries and Fishing Coastal Habitat Resource Information System data and refer to all types of fishing (commercial and recreational) on reef habitats only. Estimates do not include netting or trawling effort in inter-reef areas.

| 17.4b | Inshore | Offshore |
|---|---|---|
| **Far Northern** | High alkalinity super-saturation<br>High cloud cover<br>Low sea temperature warming (approximately 0.3°C since 1903)<br>Low cyclone frequency<br>Low fishing effort<br>Few crown-of-thorns starfish outbreaks<br>Low exposure to terrestrial runoff<br>High coral species richness<br>High annual mean temperature tolerance in corals | High alkalinity super-saturation<br>High cloud cover<br>Low sea temperature warming (approximately 0.3°C since 1903)<br>Low cyclone frequency<br>Low fishing effort<br>Few crown-of-thorns starfish outbreaks<br>Low exposure to terrestrial runoff<br>High coral species richness<br>High annual mean temperature tolerance in corals<br>Low seasonal temperature amplitude<br>Cooling through upwelling, mixing from currents and swell, shading from steep slopes<br>Conditions less suitable for macroalgal growth |
| **Northern** |  | Cooling through upwelling, mixing from currents and swell, shading from steep slopes<br>Conditions less suitable for macroalgal growth |
| **Central** |  | Low exposure to terrestrial runoff<br>Cooling through upwelling, mixing from currents and swell, shading from steep slopes<br>Conditions less suitable for macroalgal growth |
| **Southern** |  | Low exposure to terrestrial runoff<br>Cooling through upwelling, mixing from currents and swell, shading from steep slopes<br>Poor conditions for macroalgal growth |

***Figure 17.2*** *Map of the predicted vulnerability of coral reefs of the GBR to climate change*[f]



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[f] Based on a qualitative preliminary assessment of the spatial distribution of the main climate and other environmental factors that are likely to affect the degree of risk and resilience (see Tables 17.4 a and 17.4 b). Importantly, this assessment is conceptual rather than quantitative, and there are no firm boundaries of regions, hence the shades of risk are indicative rather than quantitative

At within-reef scales, spatial differences in vulnerability appear limited. Windward and leeward sides appear to show a similar number of risk factors and resilience factors, and shallow areas have only slightly more risk factors compared to deep areas (Table 17.5 and Figure 17.3). However, sheltered and poorly flushed lagoons and embayments appear to be most exposed to risk factors, and have the lowest resilience factors with regards to bleaching, whereas well-flushed flanks are probably best protected against damage from bleaching[116]. In contrast, well-flushed areas may be the least protected against ocean acidification, as locally buffering dissolving calcium carbonate would be flushed away and unable to protect calcifying biota[20].

In summary, the spatial distribution of risk factors suggests that long-term vulnerability is greatest in inshore regions of the southern and central GBR, and in shallow waters, lagoons or bays. In contrast, resilience is highest in offshore reefs of the far northern GBR and on well-flushed flanks (Tables 17.4 and 17.5). These preliminary predictions were compared against observed bleaching patterns in the

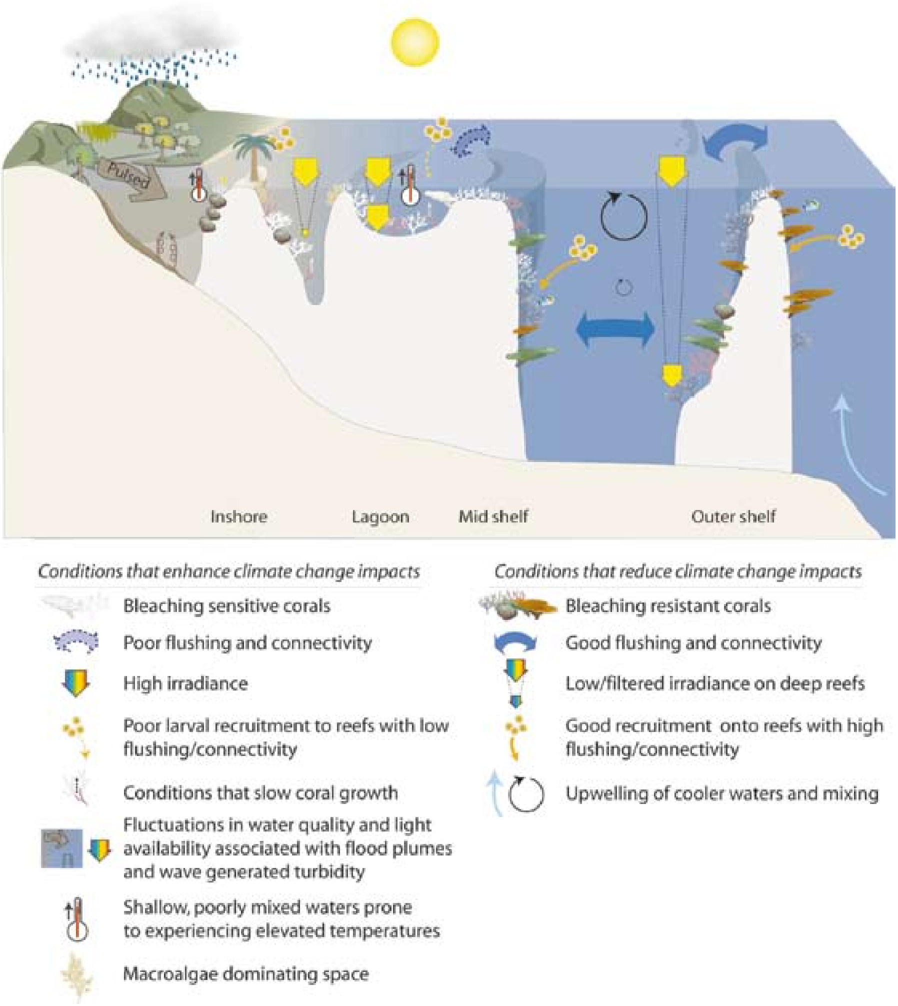
***Table 17.5*** *(a) Risk factors: local conditions that increase vulnerability to climate change impacts within coral reefs (b) Resilience factors: local conditions that reduce vulnerability of climate change impacts within coral reefs.*

| 17.5a | Shallow | Deep |
|---|---|---|
| **Front (windward)** | High irradiance<br>Fast macroalgal growth (inshore)<br>Sensitive communities | Slow coral growth, slow recovery<br>Sensitive communities |
| **Back (leeward)** | High irradiance | Slow coral growth, slow recovery<br>Sensitive communities<br>High levels of sedimentation |
| **Lagoon and bays** | High irradiance<br>Low flushing – high sea temperature heating<br>Low larval settlement<br>Slow coral growth, slow recovery | Low flushing, wave mixing – greatest sea temperature heating<br>Low larval settlement<br>Slow recovery (very slow coral growth)<br>High levels of sedimentation |
| **Flank** | High irradiance | |

| 17.5b | Shallow | Deep |
|---|---|---|
| **Front (windward)** | Fast growth<br>Low sedimentation<br>High wave mixing | Low irradiance |
| **Back (leeward)** | Resistant communities (inshore) | Low irradiance<br>Poor conditions for macroalgal growth |
| **Lagoon** | Resistant communities | Resistant communities<br>Low irradiance |
| **Flank** | High flushing<br>Fast growth | Resistant communities<br>Low irradiance |

1998 and 2002 events. Arial surveys showed that bleaching was more severe inshore than offshore, with 74 versus 21 percent of reefs bleached in 1998, and 72 versus 41 percent in 2002[8]. Offshore reefs in the far northern and the southern (Swains complex) regions experienced little bleaching, and inshore reefs in the far northern region showed slightly less bleaching than inshore reefs in the central and southern regions. Satellite-derived 3-day maximum sea surface temperatures explained 73 percent of the variation in the occurrence of bleaching between reefs, and the odds of bleaching increased 5.7-fold with every degree increase in 3-day maximum temperatures[8]. Underwater surveys showed that bleaching damage was more severe inshore than offshore, and more severe in shallow than in deeper waters, and that less bleaching occurred in well-flushed channels than in lagoons and ponding back reefs[21]. It is obvious that a better system understanding and more quantitative data need to be considered to test and verify the preliminary predictions made here.

***Figure 17.3*** *Overview of some of the main physical, spatial and biological factors that affect the vulnerability of coral reefs to climate change*



## 17.5 Linkages with other ecosystem components

Although coral reefs represent only 6 percent of the area of the GBR Marine Park, they are vitally connected to other GBR habitats including mangroves and salt marshes, seagrass meadows and estuaries, as well as pelagic environments[15] (Sheaves et al. chapter 19). Reefs act as barriers against oceanic waves providing shelter that is critical to mangroves, seagrasses and salt marshes. Loss of connectivity, both physically and ecologically, will affect the movement of nutrients, pelagic organisms (particularly planktonic larvae and invertebrates), as well as the survival and dispersal patterns of eggs, larvae and juveniles of reef species, compromising ecosystem functions. Flow-on effects to coral reefs are to be expected as other ecosystem components are deleteriously impacted by climate change, and ecosystem diversity and functions decline.

Pelagic environments (primarily through resident plankton) directly support a wide variety of suspension feeding organisms and planktivorous fish on coral reefs. Planktivorous fish are the largest trophic category of fishes by weight and number at shallow depths on GBR coral reefs (McKinnon et al. chapter 6). Similarly, many coral species rely on plankton and suspended particulate material as a primary food resource. As primary productivity of plankton communities is affected by changes in sea temperature, rainfall patterns, runoff and ocean circulation, the transport and availability of nutrients to reefs will decline. This will in turn decrease food quality and quantity for higher trophic levels with a resultant decline in abundance and diversity of other species on reefs (Kingsford and Welch chapter 18).

Mangroves and salt marshes, seagrasses and wetlands are a complex connected mosaic of habitats that are important nursery and juvenile habitats for many coral reef species. The movement of these species result in the transfer of materials between habitats through grazing, predation, and excretion (Waycott et al. chapter 8, Lovelock and Ellison chapter 9). Material exchange between mangroves, salt marshes and seagrasses and other adjacent habitats are critical for the survival of many reef species. Therefore loss of seagrasses or mangroves, or changes in productivity, are likely to affect reef species that spend part of their life history in these habitats and may be important members of the reef trophic structure. In addition, sediment filtering and trapping, nutrient cycling and substrate stabilisation are important functions of these habitats that may be compromised by climate change (Waycott et al. chapter 8, Lovelock and Ellison chapter 9). The implications for reefs are that any increased delivery of sediment or nutrients to inshore reefs reduces water quality and threatens reef resilience and recovery after disturbance.

## 17.6 Recommendations

### 17.6.1 Potential management responses

Concerns about the status and future of coral reefs are increasing. Coral reefs are shaped by disturbance regimes, and storms and freshwater floods have exerted major influence on the ecology of coral reefs throughout millennia. However, climate change, through the rapid increase in atmospheric concentrations of greenhouse gases like carbon dioxide, is changing the rate of disturbance as well as changing baseline climate conditions. This in turn is exacerbating human related disturbances such as fishing, destructive fishing and water pollution[10]. The frequency and severity of disturbance of coral reefs is unprecedented in modern times, and several global assessments conclude that about

27 percent of the world's reefs have been damaged or destroyed, while a further 50 percent have already been severely degraded as a consequence of human activity[104,123]. Should ocean pH continue to decline while temperatures continue to rise as a result of anthropogenic greenhouse gas emissions, then reef structure will be lost as carbonate dissolution and coral bleaching continue to increase both in severity and frequency. A dramatic loss in reef biodiversity appears inevitable at atmospheric $CO_2$ concentrations approaching 500 parts per million. Given that impacts on many other ecosystems also become extreme at 450 to 500 parts per million, limiting emissions to below this point is critical for coral reefs.

There is little doubt that coral reefs of the GBR are particularly vulnerable to climate change. Disturbance by climate change, when combined with other existing human stressors, is likely to further degrade this valuable ecosystem, and threaten resilience. Effective management strategies to reduce the impacts of climate change and promote resilience are essential to ensure the future survival of coral reefs. It is important to understand that these management responses are not a solution to the problems faced by coral reefs under human-driven climate change. They must therefore be part of a strategy that involves stabilising atmospheric $CO_2$ at concentrations less than 450 to 500 parts per million. Strategies to enhance reef resilience have started to emerge[100,127], and are briefly summarised here. Unfortunately, no strategy for addressing the effects of ocean acidification on coral reefs is presently known.

To maximise the ability of the GBR to cope with climate change, the impact of other anthropogenic stresses must be reduced. The authors recommend the following management strategies should be considered as a matter of priority:

- *Protection of water quality:* Deteriorating water quality from increased runoff of sediments, nutrients and agrochemicals from agricultural land is a major anthropogenic threat to inshore coral reefs. The *Reef Water Quality Protection Plan* aims to 'halt and reverse the decline in the quality of water entering the GBR lagoon by 2013'. Continued effective implementation of this plan is considered essential to maintain the ecological balance in coral reefs, reduce disturbance from terrestrial runoff and the consequences on coral recruitment, algal abundance and frequency of crown-of-thorns starfish outbreaks[30,11].
- *Protection of coastal habitats:* The protection of coastal habitats such as mangroves and salt marshes, estuaries and seagrass meadows will maintain key functions of these habitats. Functions such as sediment filtering and trapping, nutrient cycling and substrate stabilisation are important for addressing poor water quality and reducing sediment and nutrient delivery to GBR reefs. Protecting coastal habitats will also maintain the connectivity between these habitats and coral reefs, and the critical habitat they provide for reef species that spend part of their life cycle in these habitats[15].
- *Protection of biodiversity:* A comprehensive network of adequate and representative marine areas exist in the GBR Marine Park. There is now increased biodiversity protection with 33 percent of the GBR Marine Park designated as no-take areas, and protection of inter-reef habitats from bottom trawling in other areas. This type of protection will play a role in preventing the destabilisation of ecological balance and macroalgal proliferation after corals die, and hence assist corals to recover more quickly from disturbances. Networks of marine protected areas are generally considered an essential strategy to improve reef resilience[101], and in the GBR they will play a significant role in minimising impacts from the increasing frequency of climate change related massive disturbances.

Furthermore, some interventionist approaches have been proposed recently to lessen the direct impacts of climate change on coral reefs of the GBR. The following management strategies have been discussed:

- *Shading and mixing:* Shading by clouds or steep islands reduces bleaching damage in corals[62,83,33]. Similarly, water turbulence lessens bleaching damage[85]. Trials have begun with tourism operators on the GBR to explore the utility of shading small patches of economically important reefs close to tourist pontoons to reduce the amount of damage occurring during mass bleaching episodes. Such proposed management intervention may be effective on very small scales, protecting key sites that may have economic or other significance, but it is obviously not a solution to remediate climate impacts at an ecologically relevant scale. Furthermore, the economic viability of erecting structures like shades may become more compromised should cyclone intensities increase.
- *Transplantations:* Another local scale, coral bleaching specific strategy has been proposed by some researchers to seed the southern GBR with potentially more temperature adapted genotypes of endosymbiotic dinoflagellates and corals from the northern GBR. As numerous environmental conditions differ between north and south (eg naturally lower aragonite saturation, lower winter temperatures, different types of predators, more vigorous macroalgae), the success and ecological implications of such transplantations are unknown. Such experiments have limited application while the implications for the wider ecosystem are not reliably understood or addressed. Before any trails of this nature can be conducted, comprehensive research is needed to predict the likelihood of success and to avoid potential disruptions in ecosystem functions such as the spread of coral disease.

Alleviating the rate and magnitude of climate change pressure on species and habitats of the GBR is an essential strategy. As few obvious regional-scale strategies exist, it is an ecological and economic imperative for the world population to substantially cut greenhouse gas emissions, and slow the predicted rate and extent of change in the global climate. This requires the rapid adoption and implementation of effective greenhouse gas mitigation strategies.

### 17.6.2 Further research

Research is urgently needed to improve the ability to predict future climate change impacts on coral reefs, and integrate both natural and climate change-related stressors in future models. The following list represents top research priorities to improve our ability to assess vulnerability and predict change. A better understanding of these questions might also facilitate the development of new management strategies, and prioritisation of potential management options:

- *Understanding adaptation:* Mechanisms and time frames of acclimation and adaptation at all levels of biological organisation, from molecular to ecosystem level. This knowledge is essential to support our capacity to predict ecosystem changes in response to climate change.
- *Identifying refuges:* Mapping the main refuges from climate change for the next 30 years. Data and models are needed to test and quantify the proposed schematic latitudinal, cross-shelf and within-reef gradients in exposure and potential impacts. These refuges will be important for maintaining and supporting reef resilience, and must be given the highest level of management protection.

- *Climate change stress interactions:* Quantify the interactive and synergistic effects of ocean warming, aragonite saturation and increased storm frequency on ecosystem calcification budgets for the different regions of the GBR.
- *Climate change and other stressors:* Quantify the specific interactions and synergies between climate related ecosystem disturbance and water quality. Quantify the specific interactions between climate related ecosystem disturbance and fishing pressure. How do poor water quality and fishing pressure affect reef resilience?
- *Life history impacts:* Investigate the influence of higher water temperatures on the life history of planktonic life stages and metamorphosis in key reef organism groups.
- *Transplantation:* Investigate the likely consequences of seeding high-temperature adapted coral gametes and zooxanthellae from the northern part of the GBR on reefs in regions further south.
- *Ocean acidification and calcification:* Quantify the specific effects of changing aragonite saturation for benthic and pelagic calcifying organisms and explore adaptive mechanisms to continue calcification at lower carbonate supersaturation.
- *Extinction risk:* What are realistic rates of local and global species extinctions in response to climate change, and what are the properties of marine species that are most at risk of extinction? What would species extinctions mean for the GBR ecosystem?
- *Ecosystem stability:* The role of species redundancy in maintaining ecosystem stability and the linkages between species diversity and specific coral reef functions.

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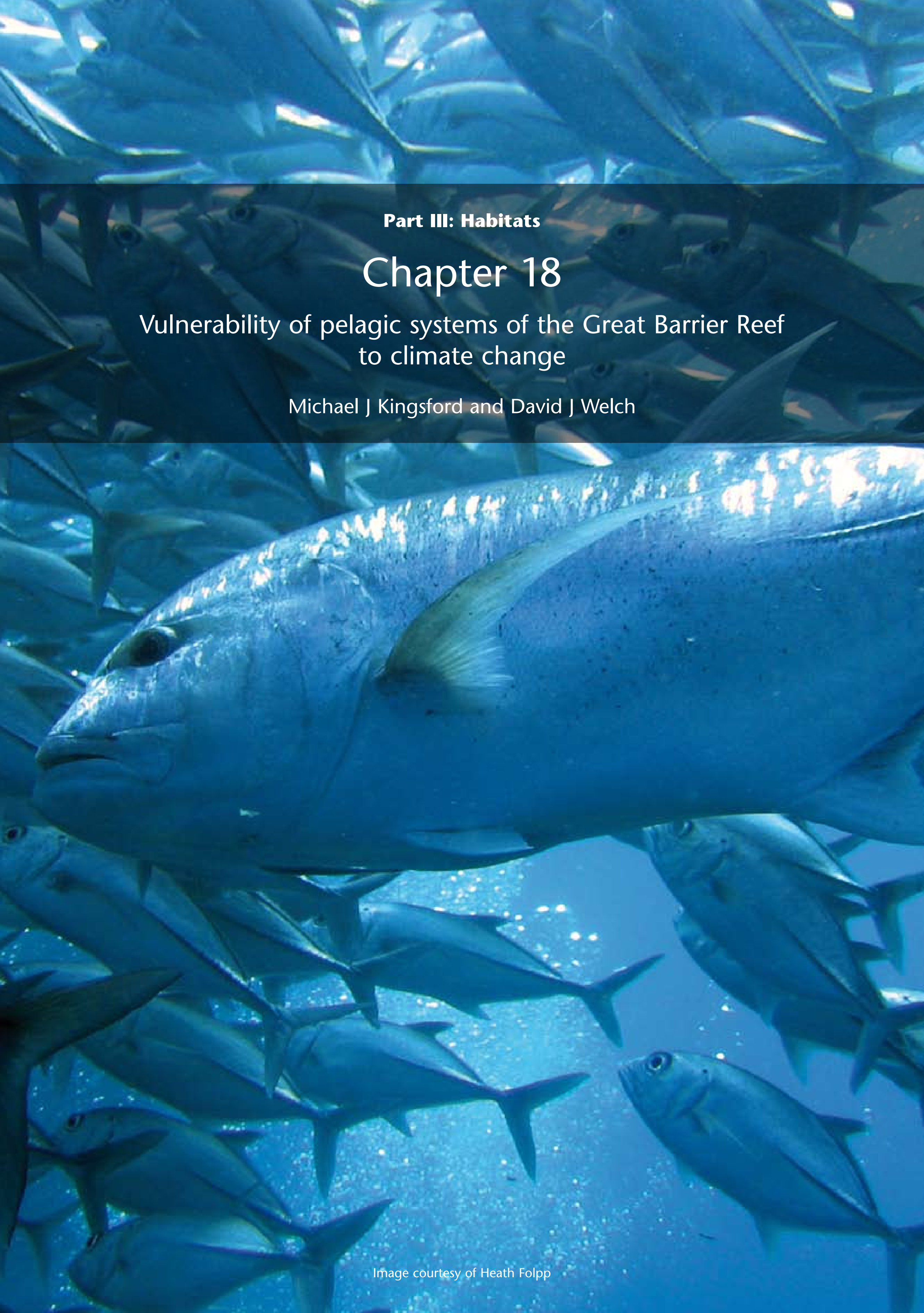


Part III: Habitats

# Chapter 18

## Vulnerability of pelagic systems of the Great Barrier Reef to climate change

Michael J Kingsford and David J Welch

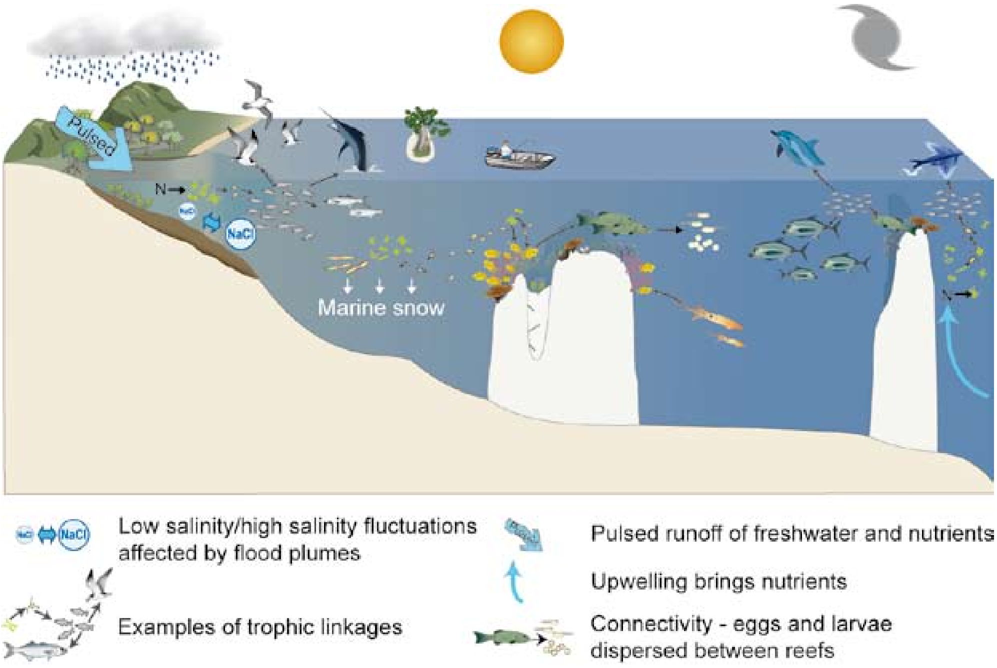
Image courtesy of Heath Folpp

## 18.1 Introduction

It is well known that physical forcing, through changes in climatic conditions, has a great influence on terrestrial[58] and marine ecosystems[4,86]. Most research in this area has focused on dominant climatic signals on scales of tens of years and at spatial scales of kilometres to thousands of kilometres for the El Niño-Southern Oscillation (ENSO) in the Pacific and the North Atlantic Oscillation. Some changes in the biogeographic patterns of pelagic assemblages, on a scale of decades, have been related to ocean warming[6]. However, there are few reliable data on long-term change and the responses of organisms to changes in pelagic environments, especially in tropical latitudes. The challenge is to extrapolate beyond relatively short time scales to climate change and its consequences for pelagic ecosystems over the longer term. How will environmental baselines change and how will organisms respond or adapt to change?

This review focuses on pelagic environments. The oceanography of the Great Barrier Reef (GBR) is dynamic and is the physical template to which organisms respond. Planktonic assemblages are the basis of pelagic food chains and they provide a rich supply of food for high trophic groups (eg fishes, birds and whales) as well as the larvae and adults of benthic assemblages (Figure 18.1). Changes in pelagic systems, therefore, cannot be viewed in isolation from other habitats (such as coral reefs). Plankton ranges from tiny viruses (less than 1 micron) and bacteria, to larger plant (phytoplankton) and animal plankton (zooplankton). Jellyfish are the giants of the plankton world and can reach

***Figure 18.1*** *Profile of the GBR from inshore to offshore showing key organisms of the tropical pelagic food chain, and physical features of the pelagic environment that influence organisms (eg upwelling and riverine runoff)*



metres in size. Planktonic assemblages support a wealth of predators. Consumers of plankton (eg small planktivorous fishes such as sprats and pilchards) support larger consumers such as squid and fishes (eg mackerels, tuna, sharks), seabirds and whales. Plankton feeders are not always small in tropical waters of Australia and the world's largest shark (whale shark), largest rays (manta rays) and marine turtles (leatherbacks) feed on plankton. Changes in planktonic assemblages, therefore, can have an impact throughout the food chain and include organisms of all sizes.

Phytoplankton are called 'autotrophs' because they use sunlight to photosynthesise sugars that are essential for life. Consumers ranging from microscopic plankton to large fishes directly or indirectly depend on phytoplankton. Phytoplankton also has a major role in the recycling of carbon dioxide ($CO_2$). For these reasons anything deleterious that happens to phytoplankton will have a cascade effect through the entire food chain. Pelagic ecosystems are well known for trophic cascades and it is generally assumed that nutrient supply and subsequent growth of phytoplankton will result in 'bottom up' control of the whole food chain[134]. Top-down effects are also possible. This has been demonstrated in lakes[93] and marine ecosystems[95,42] where predators remove zooplankton grazers, relieving grazing pressure on phytoplankton resulting in an increase in phytoplankton biomass. Changes can happen very quickly in the plankton and this will affect populations of nektonic animals.

### 18.1.1 Scope of the chapter

The aims of this chapter are as follows:

i) Give an overview of the physical environment and biota of pelagic ecosystems of the GBR.

ii) Discuss the broader significance of pelagic organisms as links between habitats, connectivity among habitats such as coral reefs, and consequences of change to existing processes (eg survival of larvae).

iii) Assess the vulnerability of pelagic habitats to climate change.

iv) Discuss the implications for management and make recommendations.

In this volume useful background knowledge to this chapter can be found in Lough (chapter 2) who provides a detailed account of projected changes in climate in the GBR, and Steinberg (chapter 3) who provides an explanation of projected changes in oceanography of the GBR. From an organism-based view, we especially recommend reviews on phytoplankton and mesozooplankton assemblages (McKinnon et al. chapter 6), planktonic viruses and bacteria (Webster and Hill chapter 5), fishes (Munday et al. chapter 12), seabirds (Congdon et al. chapter 14) and marine mammals (Lawler et al. chapter 16).

By necessity this review utilises findings from all over the world. Many paradigms concerning pelagic habitats have come from high latitude studies in the northern hemisphere[50,115] and the relevance of these to tropical pelagic habitats could be questioned. However, there are significant similarities between temperate and tropical pelagic habitats. At low latitudes, planktonic assemblages are characterised by small variations in biomass, low standing crop and high turnover rates; rather than high variation in biomass, sometimes-high standing crop and high turnover rates found at higher latitudes[133]. Although more knowledge is needed about tropical pelagic habitats, it is true that all pelagic systems are characterised by rapid change, and variation in the physical environment can have a great influence on all taxa in pelagic assemblages.

## 18.2 Description of pelagic systems

### 18.2.1 Physical environment – oceanography of the GBR

Oceanography affects the GBR at large and small spatial scales[145]. At the largest spatial scales (thousands of kilometres), major oceanic currents of the Pacific bath the GBR, affecting patterns of flow and the movement of warm and cool waters. At small spatial scales (centimetres to metres), small-scale turbulence can affect the settlement patterns of organisms such as corals. The South Equatorial Current that flows from east to west affects the oceanography of the GBR. The South Equatorial Current weaves its way as 'jets' around Vanuatu and New Caledonia before bifurcating at the central GBR. Waters flow north and south as the East Australia Current. The South Equatorial Current often enters the reef matrix, especially where the density of reefs is low[12], and influences flow within the GBR lagoon. Tides (2 to 5 metres in amplitude) flow on and off the shelf and often dominate transport of water. Complex topography generates jets, eddies and convergences and the position of these features will vary with direction of flow[70]. Wind varies in direction and strength with time of year and influences water movement and the resuspension of sediments, especially in shallow water. Wind generated movement and destructive waves can be catastrophic during cyclones. Variation in vertical physical structure (ie thermoclines and haloclines) and the input of freshwater from coastal sources also have an effect on water transport and associated particles. Across the shelf, nearshore waters are often impacted by freshwater and runoff of nutrients whereas outer shelf waters are more affected by upwelling of cooler nutrient-rich waters[35]. Anthropogenic impacts are greatest near shore where delivery of sediments, nutrients and pesticides from agricultural activities varies according to freshwater flow from rivers. Nearshore waters are most turbid due to wind related turbulence in shallow water and riverine inputs[34].

### 18.2.2 Pelagic assemblages of the GBR

#### *18.2.2.1 Viruses to jellyfishes*

Tropical pelagic assemblages are diverse and there is great variation in body size from viruses to whales. Plankton includes tiny viruses, bacteria, cyanobacteria (eg *Trichodesmium*), dinoflagellates, diatoms, copepods, larvaceans, arrow worms, larval forms of invertebrates and fishes, and tiny jellyfishes to those that are metres in length (McKinnon et al. chapter 6). The relative abundance of autotrophs varies with nutrient input and, at some latitudes, time of year. Although seasons are often ignored in tropical environments, the latitudinal range of the GBR is extensive (10 to 24° S) and seasonal change in the composition of plankton is therefore considerable.

Phytoplankton is a critical food source for zooplankton. Zooplankton include many larvae that are temporary members of the plankton (meroplankton) and those that spend their whole life as plankton (holoplankton). A multitude of developmental forms that include nauplii, intermediate stages (eg copepodites) and adult holoplankton are found. Copepods (subclass Copepoda) often dominate zooplankton samples (up to 80% of catches and there are at least 193 species on the GBR). Common genera in waters of the GBR include: medium sized *Acartia, Paracalanus, Temora* (approximately 0.7 to 1.1 mm adults), and larger *Candacia, Undinula, Eucalanus, Centropages, Labidocera, Pontella* of the order Calanoida (approximately 1 to 3.0 mm); small to medium sized *Oithona* and *Oncaea* (approximately 0.7 to 1.1 mm adults), of the orders Cyclopoida and Poecilostomatoida respectively;

and *Euterpina* and *Microsetella* of the order Harpacticoida. Other important members of the phylum Crustacea that are found in net plankton include *Penilia* (order Cladocera).

Critical links between benthic and pelagic assemblages occur through the larval forms of reef-associated organisms such as corals, crabs, crown-of-thorns-starfish, sea urchins and fishes. Invertebrates and fishes release eggs or larvae in the water column[14] and pre-settlement phases can last from about nine days for clown fish to months for taxa such as surgeon fishes and tropical lobsters. At times of the year when animals are spawning, larvae can constitute a major component of total plankton. This is especially the case for corals that have 'mass spawning' and benthic algae that have mass releases of spores into the water column[21,140]. Larvae range from the small and ciliated planula larvae of jellyfish and corals (about 0.5 mm) and the transparent brachiolaria larvae of starfish, to large and essentially nektonic pre-settlement reef fishes. The pelagic phase of surgeonfish can be over 50 mm (standard length, SL) at settlement and tank tests have demonstrated they may swim up to 120 km without food. Although some larvae do not feed in the plankton[151], most are planktotrophic and depend on planktonic food to survive. Although the larvae of many tropical taxa can be found throughout the year[73], distinct spawning seasons are typical of most invertebrate and fish taxa[87]. The majority of taxa spawn late spring to summer, the period of time when GBR waters are most likely to be impacted by warm water anomalies (Lough chapter 2).

There are few data on broad scale (ie kilometres to hundreds of kilometres) abundance patterns of plankton on the GBR. Some data indicate total plankton is most abundant in nearshore waters, followed by mid-shelf then outer waters[138]. This corroborates with a concentration of schooling planktivorous fishes that concentrate in nearshore waters[18], but the persistence of these patterns within and between years is unknown.

Gelatinous megazooplankton are spectacular predators of the zooplankton and can have a great influence on pelagic food chains. Although jellyfish are a natural part of the ecosystem their abundance is sometimes related to the health of an ecoystem, be that thermal or nutrient related[64]. For example, abundance of some jellyfish flourishes in eutrophic conditions[77]. The phylum Cnidaria includes the class Scyphozoa, represented by many large jellyfish, some of which have tentacles that extend over three metres in length (eg *Cyanea, Desmonema*; lions mane jellyfish) and they can weigh more than 10 kilograms. Others have stumpy tentacles, such as *Catostylus*, and fisheries target some of these taxa for sushi grade jellyfish (adults are up to five kg wet weight). One of the most common jellyfish in coastal waters is *Aurelia* (moon jelly), which is harmless and like most jellyfish can be found in great numbers. Densities of jellyfish can be so great at times that they are referred to as 'blooms'[77]. The deadliest jellyfish belong to the class Cubozoa and include stingers and multiple types of jellyfish that are responsible for the medical condition called Irukandji syndrome (eg *Carukia barnesi* and *Pseudoirukandji* spp.). Little is known about the ecology of cubozoans, except chirodropids (eg stinger *Chironex fleckeri*) that are abundant in nearshore waters. Polyps of chirodropids are in estuaries and the release of small medusae is thought to coincide with rain events[150]. The carybdied *Carukia barnesi* is found nearshore, while very dangerous Irukandji syndrome medusae, such as *Pseudoirukandji* spp., are most common kilometres from mainland Australia (L Gershwin and J Seymour pers comm). Anecdotal accounts suggest that the incidence of stings and observations of dangerous cubozoans has increased over the last decade and there is strong evidence for global increases in jellyfish and other gelatinous zooplankton worldwide[13,90].

Other gelatinous zooplankters have important roles in pelagic ecosystems. Siphonophores are voracious predators of plankton and are solitary or form long strings (colonies) that drift and swim by hydraulic pumping of seawater. In bloom conditions jellyfish siphonophones and comb jellies (Ctenophora) can have a significant effect on concentrations of holoplankton and meroplankton[111,112]. Other gelatinous zooplankters that form strings, but are unrelated to siphonophores, are the salps and doliolids (phylum Chordata, class Thaliacea; nine species on GBR; McKinnon et al. chapter 6). Salps can also bloom and their filtration of the water column can have a great effect on tiny plankton that form the food of larvae and other large holoplankton[152,153]. Gelatinous zooplankters are not only predators, they can provide shelter for small fishes and some invertebrate larvae[72].

Tropical waters are generally clear and low in nutrients. In contrast to temperate systems, there is generally consistent and high turnover of plankton[92]. It is often estimated that the entire biomass of phytoplankton turns over every two days (McKinnon et al. chapter 6). There are localised exceptions to low biomass, particularly with respect to blooms of plankton that are the result of riverine input and sometimes upwelling[34]. Riverine plumes, in particular, are well known for causing great variation in concentrations of plankton and related feeding conditions for larvae[45] and larger pelagic predators such as fishes[18].

### 18.2.2.2 Nekton

There is great diversity of highly mobile marine organisms in the GBR. There are approximately 12 species of squid, approximately 1500 species of bony fishes and sharks, six species of marine turtles, eight species of marine snakes (of 50 species in the Indo-Pacific), 35 species of dolphins in tropical seas, and 11 on the GBR (of which spinner (*Stenella longirostris*) and bottlenosed dolphins (*Tursiops truncates*) are the most common), one species of dugong and 16 species of whales (of which the humpback whale and dwarf minke whale would be the most common) (Munday et al. chapter 12, Lawler et al. chapter 16). Although seabirds are not technically nekton, they are regular visitors to pelagic habitats and many can dive tens of metres below the surface to capture prey (usually fishes, squid or plankton; Congdon et al. chapter 14). Although the majority of fishes are resident in the GBR, many large vertebrates are only temporary visitors that move freely in and out of the GBR depending on the time of year and the conditions they experience.

Squid are common in tropical waters (eg *Sepioteuthis lessoniana, Loligo chinensis, Loliolus noctiluca*)[62]. They are voracious predators that feed on plankton and fishes, and reproduce and die young[97]. No tropical squid lives for longer than one year[62]. Small squid have been collected at all distances across the continental shelf of the GBR[98], but knowledge of their ecology and movements on and off the shelf is poor. However, distributional data would suggest that some taxa never leave shelf waters (eg *Idiosepius pygmaeus*).

A range of small fishes, both open water and reef-associated, feed on plankton and in turn provide critical food for a broad range of bony fishes, elasmobranchs, seabirds and cetaceans. Small fishes of the families Clupeidae (herrings and sprats), Engraulididae (anchovy), Carangidae (trevallies and scad), Scombridae (mackerels) and Caesionidae (fusiliers) are important as bait fish at all latitudes on the GBR (Figure 18.2). These small fishes are the prey of larger fishes that include: scombrid (eg *Scomberomorus commerson*, narrow barred spanish mackerel; *Scomberomorus semifasciatus*, grey mackerel; *Euthynnus affinis*, mackerel tuna; *Thunnus tonggol*, longtail tuna), carangid (*Elegatis bipinnulata*, rainbow runner;

***Figure 18.2*** *School fish and piscivores: a predatory spanish mackerel hunting hardy heads (Photo credit: Robert Torelli, Blue Water International)*

*Caranx ignobilis*, giant trevally; *Carangoides fulvoguttatus*, gold-spotted trevally), Coryphaenidae (eg *Coryphaena hippurus*, dolphinfish) and at the largest end of the fin-fish tree the sailfish and marlins of the family Istiophoridae (eg *Istiophorus platyerus*, sailfish; *Makaira mazara*, black marlin).

Open water sharks of the GBR are broad ranging[57] and have a diverse diet that includes squid, small and large bony fishes and other sharks[53] (Chin and Kyne chapter 13). Whaler sharks (Carcharhinidae) are common in open water and fast-moving sharks of the Lamnidae (eg *Isurus oxyrinchus*, mako shark) will feed on fish as large as marlin. Large but relatively docile planktivores include whale sharks (*Rhincodon typus*) and manta rays (*Manta alfredi*). Many of these large elasmobranchs have been demonstrated to move outside the GBR and sometimes between countries (eg whale sharks move from Ningaloo Reef in Western Australia to Indonesia). Juvenile whale sharks are thought to aggregate off Ningaloo Reef during the Austral autumn to feed on a rich supply of euphausids and other planktonic food such as coral spawn[130,142]. There is some evidence that numbers of sharks are influenced by ENSO, where numbers are greatest during La Niña conditions[141]. Large rays such as manta rays may also have large-scale movements that relate to reproduction, similar to cownose rays in Atlantic waters[5], but there are no data on this.

Large mammals use tropical waters of the GBR and many species of dolphin and whale are found in GBR waters (Lawler et al. chapter 16). Dolphins focus on bait fish as a food source and are found in nearshore to offshore waters over the continental shelf. Although some dolphin populations are resident on scales of less than 10 km$^2$, many whales only use reef waters at certain times of the year. Humpback whales give birth during the Austral winter before mating and returning to Antarctic waters. Similar migrations have been discovered for Arnold's minke whales that are common in mid- and outer-shelf waters of the GBR. Baleen and toothed whales (Odonticeti) are sometimes observed feeding on schools of bait fish (Lawler et al. chapter 16).

## 18.3 Significance of pelagic organisms in the GBR

### 18.3.1 Food for larvae

Trophic cascades in pelagic ecosystems are likely to be strongly bottom-up with ample evidence in different environments for strong linkages between phytoplankton, zooplankton and fish populations[103]. Larval invertebrates, squid and fishes from all environments on the GBR as well as those from coastal systems, and perhaps the deep seas adjacent to the shelf, have to survive their early life history in the plankton. Some larvae will grow and eventually settle in benthic environments such as reefs, while others will grow into pelagic juveniles. Great focus has been given to understanding how organisms survive early life because it is a fundamental determinant of input to and the viability of populations[124]. It is clear that abundance of food and predators can be critical determinants of survival in the plankton (Table 18.1). The timing, types and amount of plankton produced are all important. The combination of plankton and suitable oceanographic conditions can also be critical to concentrate prey to levels required by larvae to survive.

***Table 18.1*** *Examples of hypotheses on factors in pelagic habitats that affect numbers of larvae that survive to recruit to adult populations. Hypotheses focus on the importance of planktonic food, predators, oceanography or a combination of factors*

| Hypothesis | Scenario | Source |
|---|---|---|
| Match-Mismatch | The survival of fish larvae is greatest when production of larvae through spawning of adult fish matches the production of larval food | Cushing[26] |
| Vertical stability | Thermoclines are essential to aggregate planktonic food into concentrations that allow fish to survive | Lasker[85] |
| Upwelling/turbulence | Level of upwelling and disturbance influences encounter rates of larvae with food which will influence survival of larvae | Cury and Roy[25] |
| Stable retention areas | Oceanographic features retain larvae so that they recruit to adult populations. Retention areas prevent expatriation of larvae and the size of retention areas influences population size. The presence of a retention area is more important than concentrations of food. | Sinclair[123], Lobel and Robinson[88] |
| Larval transport by internal waves | The frequency and location of internal waves will determine the number of invertebrates and fish larvae that return to coastal environments | Pineda and Lopez[109], Shanks and Wright[120] |
| Ctenophore predation | Introduced ctenophore blooms in the Black Sea and predation on clupeid fish larvae cause recruitment failure of fish | Kideys and Moghim[69] |

| Hypothesis | Scenario | Source |
|---|---|---|
| Jellyfish predation | The number of larvae surviving correlates with number of predators (ie more jellyfish means less larvae survive, regardless of the size of adult fish stock) | Moller[96] |
| Jellyfish predation and competition | Jellyfish consume many larvae, but they are also significant competitors for larval food | Lynam et al.[89] |
| Salp predation | Salps consume food for larvae so that larvae starve. Survival rates of larvae are higher in the absence of salps. | Zeldis et al.[153] |

### 18.3.2 Food for benthic assemblages

Plankton supports a diversity of organisms in coastal, inter-reef and pelagic habitats. Sponges, corals, anemones, ascidians and other suspension feeders feed on plankton and are critical for the input of nutrients to reefs and other habitats[116]. Many small reef fishes also feed on plankton. The densities of these fishes and their abundance has coined the term 'wall of mouths'[48], and in tropical and temperate regions they can have a measurable effect on plankton[76] and provide and important input of nutrients to reefs[118]. Important reef-associated taxa include fishes of the families Pomacentridae, Caesionidae, Serranidae (especially Anthids) and fishes that have a more facultative relationship with reefs such as the Carangidae and Scombridae. Munday et al. (chapter 12) and Hoegh-Guldberg et al. (chapter 10) provide discussion on coral reef fishes and corals. The fall-out of plankton and faeces from the water column to the benthos is also a critical component of marine sediments that deposit feeders such as sea cucumbers feed on; often called 'marine snow'[39]. Variation in the pelagic environment, therefore, will manifest itself on the substratum as variation in the input of food.

### 18.3.3 Predators

Predators of a wide range of sizes are found in the pelagic environment. Some of these organisms have the ability to influence population sizes of autotrophs or consumers and, therefore, variation in predator numbers will have a great influence on pelagic environments. Tiny plankton feed on each other. Of great significance to organisms from all environments on the GBR is predation of larvae. In many parts of the world, it is argued that numbers of predators determine the number of larvae that survive the larval phase (Table 18.1). The abundance of jellyfishes, ctenophores and siphonophores for example may have a great influence on the survival of fish larvae. Large gelatinous organisms also have other roles in pelagic ecosystems such as providing shelter for a host of larval invertebrates and fish[72]. It has been argued that there is a positive relationship between the abundance of large predatory jellyfish and the recruitment of small fishes that utilise the jellyfish as shelter[49]. Jellyfish predation can also result in top-down effects, for example Fock and Greve[32] modelled a pelagic food web where small ctenophores and copepods are known to eat a dinoflagellate responsible for red tide (*Noctiluca scintillans*). The model indicated that predation by scyphozoan jellyfish on ctenophores and copepods reduced predation pressure and this could facilitate blooms of the dinoflagellate.

There is experimental evidence for this in Australia (K Pitt and Kingsford unpublished data). This type of cascade could become more common with global increases in numbers of gelatinous zooplankton in coastal waters[13].

Large predators from the pelagic environment affect other environments and generate complex trophic links. Piscivorous fishes (especially from the Carangidae and Scombridae) and dolphins, for example, commonly prey on reef and estuarine associated fishes. Some large predators are closely associated with reefs (eg Serranidae[71]) and consume pelagic prey while others are open water taxa that often move in response to food and/or temperature[86] where these two factors are sometimes correlated. Intense predation by both reef-associated and open water taxa can have significant effects on populations of prey.

### 18.3.4 Bait fish: a critical resource

Bait fish are a critical resource for many consumers including squid, fishes, seabirds and marine mammals[18]. Small planktivorous school fish are found across the GBR and they are a critical resource to larger fishes from all environments[71]. There are 'hot spots' or billfish grounds in the GBR lagoon where large numbers of planktivorous school fish aggregate. Mangrove-lined bays adjacent to the GBR lagoon are highly productive and are called Effective Juvenile Habitats[28]. These grounds are considered important for a range of taxa and include the following regions: Cairns (16.8° S, 145.7° E), Dunk Island (17.8° S, 146.2° E) and Cape Bowling Green Bay (19.3° S, 147.4° E). Nutrient rich waters from mangroves and associated creeks enter coastal waters and enhance primary and then secondary production. Coastal eddies entrain this production and maintain the geographic stability of nursery areas.

Bait fish move throughout the GBR lagoon during the year. In winter, great aggregations of clupeid, carangid and scombrid bait fish and teleost, elasmobranch, avian and cetacean predators occur in billfish grounds[18]. Juvenile black marlin and adult sailfish target large surface aggregations of bait fish. Gut content data demonstrate that northern pilchard (*Amblygaster sirm*) and golden-lined sardines (*Sardinella gibbosa*) compose 95 percent of the diet in the majority of black marlin. Sailfish also consume many pilchards (57% of the diet), as well as larval monacanthids and balistids[18]. Marine mammals such as dolphins and whales also focus on large schools of small planktivorous fishes (Lawler et al. chapter 16). Many of the larger piscivores move outside the GBR once they have spawned or grown large enough to leave GBR nursery areas, thus connecting with open ocean environments. These predators are therefore reliant on adequate supplies of bait fish as their primary food source and represent an important link at the top of the food chain (Figure 18.3), and many species in turn support fisheries of importance on the GBR.

Seabirds such as terns, mutton birds, shearwaters and boobies are abundant on coral cays and granite islands of the GBR (Congdon et al. chapter 14) and use these locations as roosting and breeding sites. Near and abundant prey is usually a prerequisite for the successful survival of chicks where they feed on small clupeid fishes such as *Spratelloides robustus* as well as anchovies (*Engraulis* spp.). Adults make long distance forays from isolated reefs inside and outside of the GBR where complex topography facilitates good conditions for feeding[36].

***Figure 18.3*** *Baitfish are a critical source of food for piscivores: Golden trevally patrolling a school of bait fish (hardy heads) (Photo credit: Robert Torelli, Blue Water International)*

## 18.3.5 Fisheries

Fishers are effective predators in multiple habitats of the GBR. In some parts of the world overfishing has resulted in fishing down the food chain[64]. Overfishing has a direct effect on fishes, but can also cause trophic cascades in pelagic systems. For example, overfishing of plankton feeding fishes along the coast of Angola resulted in great population growth of gelatinous zooplankton that thrive on the additional prey[90]. Commercial and recreational fishers take fishes from the GBR lagoon and adjacent habitats such as estuaries. Reef fish, pelagic fish and fish from coastal environments are taken (Table 18.2). Fisheries have a direct ecological impact on target species and potential indirect positive affects on prey taxa. In addition, they are of considerable social and economic significance to the region.

Several commercial fisheries on the GBR target pelagic species ranging from net fisheries near the coast to line fisheries operating throughout much of the GBR. Spanish mackerel represents an important line fishery on the GBR worth approximately A$2 million annually with an annual harvest of about 600 tonnes (Table 18.2). GBR line fisheries also take shark mackerel, mostly as bycatch, and not currently in significant quantities. Other commercial fisheries that take pelagic species on the GBR are net fisheries operating in nearshore environments and take species such as grey mackerel, carangids, queenfish, pilchards, sardine, garfish and several shark species.

Recreational fishing is a significant pastime on the GBR with Queensland residents spending approximately 4.6 million days fishing during the period May 2000 to April 2001[52]. Recreational fishers using the GBR contribute about A$623 million to the Australian economy annually[2]. Mackerel species represent one of the most highly targeted recreational species groups. Commercial and recreational GBR fisheries also target a suite of reef and inshore species representing significant social and economic importance (Munday et al. chapter 12, Sheaves et al. chapter 19, Fenton et al. chapter 23).

***Table 18.2*** *Commercial and recreational catches of fishes and invertebrates taken on the GBR*. Catch in tonnes (unless specified), value in millions of Australian dollars; commercial data from 2005[a], except data for coral trout from 2005–2006 and sourced from ABARE[1]; year for recreational data as listed[16,52,113]. No data available designated by nd*

| Common name | Species | Commercial Catch ($) | Recreational Catch (year) |
|---|---|---|---|
| **Pelagic taxa** | | | |
| Spanish mackerel | *Scomberomorus commerson* | 249.3[†] ($1.746) | 406 (2003) |
| Grey mackerel | *Scomberomorus semifasciatus* | 181.1 ($1.087) | 12 (1995) |
| School mackerel | *Scomberomorus queenslandicus* | 29.6 ($0.178) | 43 |
| Spotted mackerel | *Scomberomorus munroi* | 27.8 ($0.167) | 70 |
| Garfish | Hemiramphidae | 74.3 ($0.446) | 5.2 (2001)[§] |
| Shark mackerel | Grammatorcynus bicarinatus | 43.2 ($0.259) | nd |
| Pilchards/Sardine | *Sardinops* sp. | 6.1 ($0.012) | nd |
| Trevally unspecified | Carangidae | 90.8 ($0.363) | 235.2 (2001)[§] |
| Queenfish | *Scomberoides* sp. | 78.2 ($0.235) | nd |
| **Reef taxa** | | | |
| Coral trout | *Plectropomus leopardus* | 1134.0[‡,§] ($34.020) | 386 (2005)[§] |
| Red throat emperor | *Lethrinus miniatus* | 300.0[#] ($1.501) | 118 (2005)[§] |
| Red emperor | *Lutjanus sebae* | 29.3 ($0.264) | 232 (2005)[§] |
| Spangled emperor | *Lethrinus nebulosus* | 16.9 ($0.102) | nd |
| Snapper | *Lutjanid* sp. | 23.0 ($0.184) | approx. 850 (2005)[§] |
| Tropical rock lobster | *Panulirus ornatus* | 210.0 ($4) | nd |
| **Reef, inter-reef and open water** | | | |
| Shark | *Unspecified* | 657.7 ($3.946) | approx. 105 (2001)[§] |
| **Coastal Taxa** | | | |
| Blue swimmer crab | *Portunus pelagicus* | 29.8 ($0.192) | 200 (1999) |
| Mud crab | *Scylla serrata and Scylla olivacea* | 539.9 ($5.669) | 1000 (1999) |
| Barramundi | *Lates calcarifer* | 199.9 ($1.399) | 275 (1999) |
| Tiger prawn | *Penaeus esculentus* | 1619.1 ($24.287) | nd |
| Eastern king prawn | *Penaeus plebejus or latisulcatus* | 1331.1 ($14.857) | nd |
| Banana prawn | *Penaeus merguiensis* | 348.0 ($3.132) | nd |

* Most of these taxa are important in the recreational fishery but there are few data on catches

† From 2004 Total Allowable Commercial Catch (TACC) capped at 619.5t

‡ from 2004 TACC capped at 1350t

# from 2004 TACC capped at 700t

§ estimates for all QLD

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[a] Queensland Department of Primary Industries and Fisheries commercial logbook data, http://chrisweb.dpi.qld.gov.au/chris/

Collectively the commercial and recreational fishing catch and effort for pelagic species on the GBR is relatively modest by international standards. However, locally they represent important industries both socially and economically. Just as impacts on the pelagic environment attributable to climate change may have an impact on the populations of bait fish species and those that prey on them, there would also be flow-on impacts to fisheries that target these species either commercially or recreationally. Unless these fisheries are monitored closely over the coming years of climate change, impacts on pelagic species populations may develop unchecked.

Some bony fishes and sharks have very large home ranges or are highly migratory. Consequently they are often fished immediately outside of the GBR by Australian and international vessels[74]. Fishing impacts or climate stressors outside of the GBR therefore, may affect the size of pelagic populations within the GBR. This is certainly true of large pelagic fishes such as marlin and some sharks.

### 18.3.6 Tourism

Many pelagic organisms represent the charismatic megafauna of tropical marine ecosystems and often are a focus of GBR tourism, which as part of regional tourism contributes AU$6.1 billion to the Australian economy[2]. Tourist operations have tours to sites such as the 'cod hole' on the northern GBR to observe large site-attached serranids. Sites with abundant reef sharks are also popular (eg Osprey Reef in the Coral Sea). Open water fauna including sharks and mammals also attract significant tourism attention. Tourists keenly seek observations of whales and operators take them to observe migrating humpback and minke whales.

## 18.4 Physical environment effects on pelagic organisms

Pelagic organisms interact with the physical environment. Therefore, it is not surprising that the physical environment has a great influence on fauna and variations in physical aspects of the environment will alter assemblages (Table 18.3). This is especially true where organisms are intolerant of variation outside a narrow range of conditions (eg temperature: stenothermal organisms). The physical environment can influence patterns of growth, mortality, movement, reproduction, recruitment and assemblage composition. Key physical factors include: oceanography (current strength and direction), sea level, sea temperature, ocean chemistry, ultraviolet radiation, nutrient enrichment, rainfall, salinity, wind and cyclone events. For the purposes of this chapter we are nesting rainfall (and related salinity changes), upwelling, winds and cyclones within nutrient enrichment, as all of these physical factors will have an impact on nutrient levels. Rainfall not only affects nutrient levels through runoff but can also cause low salinity waters that can kill some organisms. For example, benthic phases of some jellyfishes die in salinities of less than 12 practical salinity units (psu)[77]. Cyclones can also have significant destructive effects on reef habitats and associated organisms.

***Table 18.3*** *Physical changes to pelagic habitats of the GBR that can affect biota. Some of the sources of change listed correlate with each other (eg cyclones will alter rainfall). Indication of predicted changes are in short (next 20 years) and long term (beyond 20 to 100 years) (Source Lough chapter 2)*

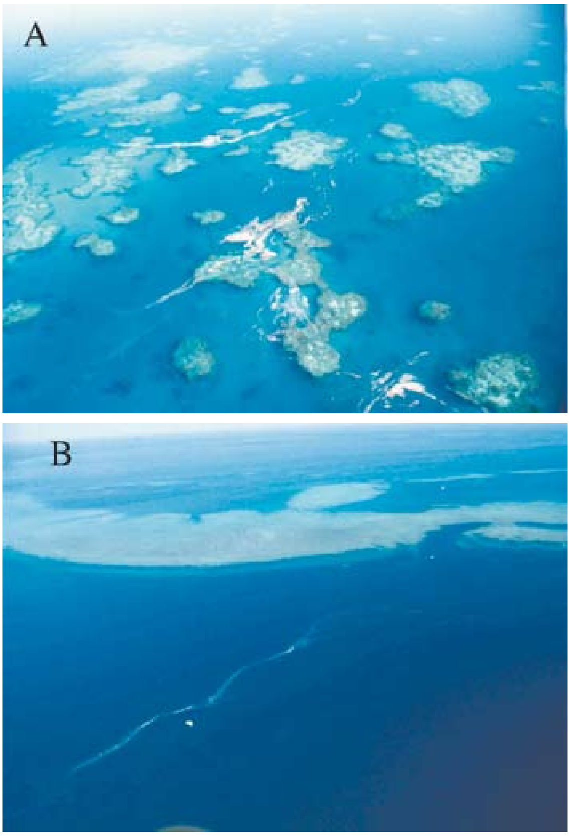
| Source of change | Scenario |
|---|---|
| Oceanography | Changes in current strength and direction; some changes in current strength are expected. |
| Change in sea level | Inundation of established coastal habitats such as mangroves and seagrass beds. An increase of up to one metre is expected in the long term. Current rates of increase are 2.9 mm per annum, but sea level would increase significantly with catastrophic melting of ice caps. |
| Temperature | Changes in average temperature will influence the size and duration of hot spots. Average increases of 1.6°C long term. There are no predictions on hot spots. |
| Acidification | A reduction in pH as a result on increased levels of dissolved $CO_2$. Decrease of 0.5 pH units is expected over the next 100 years. |
| UV radiation | Increased exposure to UV radiation; variation in short and long terms not expected to be great. |
| Rainfall and clouds | Increased residence time of warm water on the GBR could result in increased evaporation and accumulation of clouds. Onshore winds would result in greater rainfall and input of low salinity water; but predictions do not suggest a great increase in rain. |
| Upwelling | Upwelling frequency, duration and intensity along the shelf break; no predictions, but wind would affect upwelling. |
| Wind | Changes in strength and direction of wind would alter currents, upwelling and rainfall. No predicted change in wind for the short or long term, but see cyclones. |
| Cyclones | Increased intensity and frequency of cyclones. Changes in wave height and increased potential for habitat destruction; extreme rainfall and freshwater input to coastal environments which is toxic to many organisms (low salinity), increased mixing of surface layers resulting in localised change in temperature. Long- and short-term predictions show little change in cyclone behaviour. |

### 18.4.1 Oceanography

Currents connect habitats on the GBR through the transport of larvae and nutrients, and influence the movements of patches of planktonic organisms. In addition, currents influence the genesis of planktonic assemblages. For example, upwelling will transport nutrient rich waters into the photic zone. The subsequent growth of phytoplankton will in turn influence production of consumers (McKinnon et al. chapter 6).

Most benthic organisms have a larval stage that spends time in the pelagic environment. Currents can favour repatriation to areas where larvae were spawned (source) or expatriate them (sink). Oceanography clearly affects the connectivity of benthic habitats such as reefs that are separated by expanses of shelf waters. This is seen dramatically during the mass spawning of corals[101,140] where many reproductive products are dispersed among reefs separated by hundreds of metres to kilometres (Figure 18.4). Although models have predicted that larvae can disperse over great distances[65,137], it is clear that the probability of broad dispersal will depend on currents as well as the mobility and sensory capability of larvae[78]. Recent studies have indicated that a substantial proportion (20 to 30%) of at least some taxa may return to source reefs[66,67]. Despite high rates of settlement to source reefs by some taxa[37], there is still some dispersal among clusters of reefs[24]. The strength and direction of currents will influence the position of source and sink reefs[20] and a change in currents may require a response by managers to consider marine protection regimes.

***Figure 18.4*** *Connectivity of reproductive products among reefs on the central GBR.*
*A. Patch reefs in the lagoon of Bowden Reef (altitude 300 metres), coral spawn among reefs separated by tens to hundreds of metres, slick area 200 to 500 metres long*
*B. Stanley reef (altitude 1500 metres), coral spawn slicks among reefs, shown boat is eight metres long and the slick is two to three km long (Photo credit: Bette Willis)*



Oceanography will also influence the distribution of patches of plankton. For example, larvae of pelagic fishes are transported by currents that are important for retaining or transporting larvae to suitable nursery areas. Thermal signatures of patches may correspond to a unique plankton assemblage on and off the shelf[44], while nekton may respond to thermal structure[86], a potential sign that conditions are good for feeding. Climatic factors that change the direction and strength of currents therefore, would alter patch dynamics on the GBR.

Stratification of the water column influences the distribution and abundance of plankton and can have a great influence on the distribution of planktonic food and the nekton that feeds on it. Although shelf waters of the GBR are often well mixed, stratification can result from freshwater input and waters are stratified immediately off the shelf break (Steinberg chapter 3). Changes in stratification can alter patterns of plankton biomass[122] and the degree of stratification is influenced by climatic factors.

### 18.4.2 Sea level

Sea level changes with phase of the tide and, tidal ranges of 1.7 to 6 metres are typical on the GBR. Tides combined with bathymetry are primary drivers of the physical oceanography of the GBR and influence transport of nutrients, plankton and nekton and the advection of larvae as well as influencing organisms with intertidal distributions (Lovelock and Ellison chapter 9). However, the entire tidal base-line can alter with changes in sea level.

Organisms of the GBR have dealt with previous changes in sea level. Five thousand to twelve thousand years before present the current continental shelf was not immersed and as recently as 1000 years before present sea level was one metre higher than it is now. It is predicted that sea level will rise approximately one metre within the next 100 years. Organisms with narrow nearshore depth ranges would be most affected. Benthic organisms such as mangroves have moved seaward or further inland with historical changes in sea level[144]. For pelagic organisms, changes in nearshore sea level could have a great affect on nearshore production levels, the effectiveness of nursery areas, turbidity and changes in currents due to alterations to bathymetry and related water movement.

### 18.4.3 Temperature

Variation in water temperature affects many aspects of the biology of pelagic organisms, including: timing and duration of phytoplankton blooms; spawning of adults (eg fishes[121], egg size[82], survival of larvae[75], duration of larval phase[43]); growth of larval, juvenile and adult forms (eg squid[63], tropical wrasse and other reef fishes[127]); and movements and distribution of adults[86]. Temperature has also been shown to influence the distribution, abundance and growth of mesozooplankton and phytoplankton[115], the abundance and distribution of planktonic pathogens, and the occurrence and virulence of disease (Webster and Hill chapter 5).

Biogeographic patterns and growth of most marine organisms are affected by temperature[22]. Range changes in response to increases in temperature, have been demonstrated for marine fishes elsewhere[107]. In summer, normal latitudinal temperature variation from Torres Strait to the southern GBR can be 4 to 5°C (ie 25.5 to 29°C). Temperature varies with time of year, especially at high latitudes on the GBR, so some tolerance of variation in temperature is apparent. On the southern

GBR, temperatures range from 18 to 29°C during the year. Local effects that influence temperature include warming in lagoons[3], upwelling and the input of freshwater[145]. Upwelling will generally cause low temperature anomalies, while freshwater can be either warmer or cooler than the ocean and this generally depends on the time of year. Patches of warm water can pool at various locations for days to weeks based on activity of the South Equatorial Current and related ENSO effects, as well as interaction with local tides. Over the last two decades, patches of water greater than 31°C have been resident on coral reefs for long enough to cause coral bleaching.

Patches of warm water affect the distribution and recruitment of nekton. The distribution and abundance of pelagic fish species are strongly linked to temperature regimes. For example, highest catches of skipjack, the world's most prolific tuna species with respect to fisheries, comes from a 'warm pool' in the western equatorial Pacific. Further, spatial shifts in skipjack populations have been linked to large spatial displacements of this warm pool that occurs during ENSO events[86]. This has also been found for other tuna and billfish[148].

The shift in the distribution of round sardinella (*Sardinella aurita*) in the western Mediterranean Sea has been shown to correlate with changing sea temperatures, with temperature also explaining areas of high abundance and high fisheries landings[119]. Perry et al.[107] also demonstrated similar changes in a number of exploited and non-exploited North Sea fish species with changes in distribution by both latitude and depth. There are also indications of this occurring in the Bering Sea with a northward shift in the range of some fish, bird and mammal species[128].

Large pelagic species tend to show a consistent vertical stratification with dolphin fish occupying surface layers, marlin in the surface mixed layer, yellowfin tuna in the thermocline layer, bigeye tuna below the cooler thermocline and swordfish in the deeper cold waters[56]. Patterns in the geographical and vertical distribution of tuna and billfish species are strongly linked to temperature (eg Pacific bluefin[79,80], yellowfin tuna[106,27], skipjack[106], black marlin[46,17]. Worm et al.[148] concluded that sea surface temperature was the strongest predictor for pelagic predator diversity and density globally.

Spanish mackerel (*Scomberomorus commerson*) represent the most significant pelagic fishery in GBR waters. As an epipelagic shelf species, spanish mackerel are found the length of the GBR and are thought to carry out seasonal migrations along the GBR coast[131], with their range extending south during warmer months. Movements are thought to be related to food supply more than temperature, and the east coast population appears to tolerate a wide range of water temperatures. Other smaller mackerel include spotted (*S. munro*i), grey (*S. semifasciatus*) and shark mackerel (*Grammatorcynus bicarinatus*) that are important epipelagic predatory fish associated with reef and inshore waters and are important recreational and commercial species. Spotted mackerel are known to carry out seasonal northerly migrations during winter[7] suggesting that water temperature may be an important factor. Little is known of the influence of temperature on grey and shark mackerel. Temperature has been shown to be a significant determinant of distribution and movements of other fish species elsewhere including similar mackerel species (eg Atlantic mackerel, *Scomber scombrus*[99]).

Peck et al.[105] found that small scale variations in sea surface temperature of the southern GBR affected the foraging success of wedge-tailed shearwaters during their breeding season, providing evidence of fine scale mechanisms driving the coupling of breeding success of seabirds with pelagic prey distribution and ENSO events.

### 18.4.4 Ocean chemistry

Stable pH is critical for most marine organisms. Many species of marine plankton rely on optimal ocean chemistry conditions for development of calcareous shells, plates and skeletons[102]. Ocean chemistry can also affect the subcellular functions and physiology of respiration, growth and reproduction in marine organisms[114]. However, studies on the impact of changes in ocean chemistry on pelagic organisms are sparse.

Several studies have examined the effects of changes in water chemistry in the pelagic environment on the early development of some species but few data exist on the physiological regime requirements for individual species. It is significant though, that from geological records, current levels of ocean pH (and $CO_2$) are inferred to have been stable during the past 300 million years[15]. There has been some change over the last 200 years (a reduction of 0.1 pH units), probably due to industrialisation[114]. Development of pelagic eggs and larval stages of various marine organisms have been shown to be sensitive to changes in water $CO_2$ concentration and pH levels[47], however responses can differ among species and life stages. Ishimatsu et al.[61] examined a range of different species types and found that silver seabream (*Pagrus major*) and Japanese sillago (*Sillago japonica*) larval development was disrupted, particularly at the cleavage and juvenile stages with increased levels of $CO_2$. The authors also found that adults of the pelagic Japanese amberjack (*Seriola quinqueradiata*) died within eight hours of being exposed to seawater equilibrated with five percent $CO_2$ levels. Kurihara and Shirayama[83] found that fertilisation rates and development of two species of pelagic spawning sea urchins decreased with increasing $CO_2$ concentrations.

Photosynthesis in marine phytoplankton has been shown to decrease under increased levels of $CO_2$ (and reduced pH) resulting in lower phytoplankton biomass[136]. From experiments between latitudes of 11 and 44° N in the western north Pacific Ocean, copepod mortality increased under increasing levels of $CO_2$[135]. Although not conducted in the southern hemisphere, these studies found tolerance to $CO_2$ concentration changes was lower in shallow water, sub-tropical copepods.

Some subcellular functions, such as ion exchange and protein synthesis, are reduced under conditions of elevated $CO_2$ levels, more so in invertebrates than fish[110]. This can affect growth and survival and so ocean acidification impacts may vary between species. There are also potential negative synergies to organisms with increases in $CO_2$ concentration and increased exposure to ultraviolet radiation.

### 18.4.5 Ultraviolet radiation (UVR)

Ultraviolet radiation (UVR) is damaging, particularly to the DNA of organisms. UVR is long wavelength and can penetrate seawater to depths of 30 to 40 metres. There has been concern for phytoplankton and zooplankton at high latitudes where ozone depletion is greatest[51]. Ultraviolet B (UVB) exposure has been shown to inhibit photosynthesis in phytoplankton[84], but there is evidence that phytoplankton is more vulnerable at high latitudes than at low latitudes[51]. UVR is known to influence the composition of zooplankton communities in freshwater systems[108] and vulnerability to UVR is greatest at high latitudes.

### 18.4.6 Nutrient enrichment – upwelling, rain, winds and cyclones

Upwelling, rain, winds and cyclones can all influence levels of nutrient enrichment and will, therefore, affect primary productivity in the pelagic environment. Areas of upwelling, around the globe, are

where the highest biomass of pelagic organisms is found from plankton to large nekton. Nutrient rich waters are advected into the photic zone where the producers (phytoplankton) can utilise them during photosynthesis. Concentrations of nutrients are relatively low near the break of the GBR when compared to other parts of the world[145], but are of considerable biological importance to reef, inter-reef and pelagic habitats. Upwelling is of greatest biological relevance along the shelf break of the GBR where cold tongues of water are advected onto the shelf and in some cases may extend to mid shelf reefs[35] (Steinberg chapter 3).

Wilson et al.[143] showed that upwelling associated with El Niño conditions resulted in high chlorophyll abundance (phytoplankton) and high abundance of meso- and macrozooplankton. While down-welling associated with La Niña conditions resulted in the opposite community structure in the plankton. Further, differences between surface and deep macrozooplankton assemblages were more pronounced during down-welling conditions.

Wind direction and strength will influence the location of upwelling and the duration of upwelling. Thus, any changes in wind could perturb spatial and temporal patterns of biology (eg distributions and productivity). Wind has a major influence on the transport of waters near the surface (Ekman Layer) and this can influence the transport of larvae and other plankton as well as patterns of nutrient enrichment[145].

Cyclones impact on the surface layers of the ocean through increased mixing and alteration of water temperature, at least in the path of the cyclone, and significant damage can occur to the habitats of reef-associated organisms. In January 1998 on the southern Northwest Shelf in Western Australia, the passage of Cyclone Tiffany resulted in changes to the physical characteristics of the water column and in plankton communities[91]. Changes in both water temperature and salinity occurred but differed depending on proximity to the coast (shelf position). Changes to plankton included increased abundance and biomass of phytoplankton with higher primary production, changes in the composition of copepod species, and increased presence of larval fish species that were previously rare or absent. On the GBR, Cyclone Justin traversed the coast for several weeks in March 1997 and resulted in anomalous localised decreases in water temperature. No studies were conducted coinciding with this event that were able to detect changes in the pelagic environment, however resultant changes in catches of the two primary target species of the GBR line fishery were evident[139].

A major source of nutrient enrichment in the marine environment is from riverine inputs[38,45,145]. The input of terrestrial sediments and nutrients is known to affect the recruitment of fishes and prawns, and it is often argued that recruitment is enhanced through increased primary and secondary production as rainfall and associated riverine input increase. In addition, as riverine input increases associated flood plumes become increasingly effective as retention areas for larvae. Thus, a combination of factors may contribute to good recruitment, including high growth rates of larvae that can minimise the time they are affected by small planktonic predators. Inshore waters of the GBR are regularly exposed to riverine inputs and nutrient related biological impacts are likely to be greatest inshore and on wide ranging nekton that utilise inshore areas. Other biological effects of freshwater input can be mortality of some taxa through low salinity and high levels of turbidity that can reduce light penetration to the benthos[34].

A combination of climate factors will often affect organisms. For example, Bergenius et al.[10] concluded that UV radiation, along-shore winds and rainfall during early larval growth of fish on the GBR may influence growth, larval duration and settlement.

## 18.5 Vulnerability of pelagic systems to climate change

This chapter has described how the physical environment affects organisms and how changes in the physical environment can have multiple impacts (Table 18.4). Some aspects of the physical environment have shown little variation in the last few thousand years, but climate change has altered this pattern and will continue to do so. Changes that are significant for the pelagic environment include ocean acidification, ocean warming and resultant thermal expansion of water causing sea level rise of as much as one metre in the GBR region by 2100, which will inundate some low-lying coastal and coral reef environments. Inundation will be greater if there is catastrophic melting of the ice caps, where significantly higher sea level rise would be experienced. The exposure of organisms to UV light (a DNA destructor) will potentially change with loss of global protection through ozone depletion, though predictions for the next 100 years suggest little change in the tropics (see also McKinnon et al. chapter 6).

### 18.5.1 Spatial and temporal scales of impact

Climatic factors vary in space and time and this variation will have a great influence on the response of pelagic organisms. Although discussions often focus at global or GBR regional scales, some climatic perturbations will at times only affect some regions (eg northern or southern regions), certain distance strata (eg temperature induced coral bleaching is often greatest near the mainland; Hoegh-Guldberg et al. chapter 10), or clusters of reefs within a distance strata. Temperature is a good example of a stressor that varies in space (eg patches of warm water) and the duration of exposure will vary depending on the size of the patch and how fast it is being advected. Bender et al.[9] identified two kinds of perturbations, ‘pulse’ and ‘press’. A ‘pulse’ is a relatively instantaneous alteration after which the system returns to its previous state (eg a warm patch of water in an area for hours to a few days). A ‘press’ is a longer-term fluctuation that is sustained and can lead to significant impacts and possibly the elimination of some taxa (eg warm water resident in an area for weeks). An example of a press event on a scale of tens of square kilometres was experienced in the Keppel Islands in 2006 where there was substantial bleaching of corals. The ability of populations of pelagic and benthic organisms to recover will depend on the frequency and duration of events. It is highly likely that localised pulse and press events would be the first stage of climate change on the GBR for stressors such as temperature. Therefore, detection of climate change impacts over the next 100 years needs to consider spatial monitoring on the GBR.

### 18.5.2 Climatic stressors on the GBR

There are multiple projected changes in the physical environment with climate change and scenarios vary by physical variable and years from present (Lough chapter 2). Climate change is expected to alter current patterns in the GBR and the connectivity of populations between habitats. Sea level rise of up to two metres or more is possible and this will immerse shallow habitats, alter patterns of nearshore

***Table 18.4*** *Biological responses to changes in the pelagic environment. Many potential responses and the ability to adapt will depend on rates of change (Sources Kingsford and Gray[75], Hays et al.[50], Wolanski and De'ath[146])*

| Exposure | Oceanography | Temperature | Acidification | UV | Nutrient enrichment (Upwelling, winds, rainfall, cyclones | Sea level |
|---|---|---|---|---|---|---|
| Sensitivity | • All taxa with larvae are sensitive (the majority of fish and invertebrates on the GBR | • Thermal tolerance<br>• Viability of reproductive products<br>• Survival of larvae<br>• Patterns of growth | • High for pelagic organisms with calcium skeletons or shells (eg fishes, molluscs) | • High for some phytoplankton and zooplankton, which is the foundation of pelagic food chains<br>• Viability of pelagic eggs | • High for organisms with low tolerance for variation in nutrient levels | • Nekton that use coastal habitats for recruitment or feeding<br>• Organisms with historical spawning sites that are topographically distinct and will be altered with sea level change |
| Potential impacts | • Changes in larval transport<br>• Changes in connectivity among reefs and coastal environments (ie estuaries).<br>• Species replacements | • Range shifts<br>• Changes in spawning location and success<br>• Long-term viability of some pelagic populations<br>• Successional change in ecosystem (ie increase in jellyfishes) | • Change in planktonic assemblages that provide food for nekton (ie quantity and quality) | • Change in plankton community (diversity and abundance) | • Change in planktonic assemblages and food sources for larvae and nekton<br>• Changes in larval survival (positive for some negative for others)<br>• Changes in distribution<br>• Increased harmful blooms | • Alter nearshore habitats that are nursery areas fro pelagic taxa<br>• Change input of nutrients from coastal environments (eg detrital food chains) |

production and alter currents. Mean sea temperature and the size and duration of temperature hotspots will increase on the GBR and expose pelagic organisms to temperatures that are known to stress corals and could affect pelagic organisms (Table 18.4). Projected changes in sea temperature are +0.4 to 0.5°C to 2020 and 1.1 to 1.5°C by 2050 (Lough chapter 2). Changes in wind will contribute to changes in oceanography, altering patterns of connectivity, transport and nutrient enrichment factors such as upwelling and rainfall. Projections suggest that patterns of rainfall will remain similar with seasonal rain in the northern and far northern regions of the GBR, and stochastic rainfall in central and southern regions (Lough chapter 2). The magnitude of droughts and high intensity rainfall events are likely to be greater. For example, the stochastic element of rainfall may increase if there is a higher frequency of category 4 and 5 cyclones. Cyclones will generally affect relatively small areas of the GBR (eg a swath of 100 km), but this can result in significant local destruction of benthic habitats and changes in nutrient enrichment and temperature, especially through rainfall.

Projections suggest that currents are likely to remain similar in direction but with increases in the speed of key currents that influence the GBR likely (eg the East Australian Current; Steinberg chapter 3). Therefore the direction of connectivity of populations is likely to remain the same, but increases in current speed will influence local patterns of upwelling. Greatest variation in upwelling would be experienced on the shelf break. If current direction does change, patterns of larval connectivity will also change along with biogeographic patterns. Increased speed of the GBR lagoon current that flows from the central GBR to the southern GBR is likely to move temperature hotspots to the south faster. Currents in the northern and far northern regions of the GBR are generally slower behind reefs and longer residence times of temperature hotspots would be expected. Inshore, central and northern reefs are generally impacted to the greatest extent in bleaching events and pelagic assemblages may experience greater press perturbations of temperature as average sea temperatures and frequency of hotspots increase. The risk of ponding warm water masses is greatest on the northern GBR. Although bleaching has been recorded in the southern GBR, faster flowing currents in the GBR lagoon may move patches more quickly. Sea level rise will also change local currents, especially near the mainland where large expanses of low-lying coastal land would be inundated and local retention areas altered.

Average change of physical perturbations at GBR or global scales is not indicative of exposure for local populations. For example, warm seawater anomalies usually manifest themselves on the GBR as warm patches that only affect some parts of the ecosystem. The duration of a hotspot will vary from a pulse of a few hours to days, to a press lasting weeks to months. These anomalies can result in changes of up to five degrees (eg 26 to 31°C) that can affect pelagic organisms. It is likely in the next 20 to 50 years that some of the greatest impacts on organisms will be in patches rather than GBR-wide. Over longer time scales, the combination of increase in average temperature combined with an increase in the number, size and press duration of hotspots has the potential for greater impacts on pelagic populations.

Projections of atmospheric $CO_2$ concentrations show increases from current 380 parts per million to concentrations ranging from 540 to 970 parts per million by 2100[60]. As a result of $CO_2$ exchange with sea water[102], pH and concentrations of carbonate in sea water will change. The relationship for the absorption of $CO_2$ in sea water is also influenced by temperature[81] and there is the potential for calcification to facilitate a negative feedback on atmospheric levels[117]. A drop of 0.5 pH units over the next 50 to 100 years is predicted. This has the potential to affect intracellular processes and the

physiology of organisms and especially pelagic organisms with calcium carbonate (as for corals) or calcium phosphate in their skeleton. Plankton (ie foraminifera, coccolithophores), molluscs (eg pteropods, heteropods and squid), crustaceans (eg copepods) and fishes have calcium carbonate in their skeletons and fishes and marine mammals have calcium phosphate as bone. All of these organisms therefore, are at risk from ocean acidification[102]. We have already described how the environment affects pelagic organisms, and physical changes will also affect the biota of pelagic ecosystems (Table 18.4).

### 18.5.3 Empirical models – correlations between climatic factors and abundance

Empirical models are simple correlations between physical variables (eg temperature) and population parameters (eg abundance and recruitment). Empirical models[124] of recruitment levels versus oscillation indices have been published for a wide range of taxa including algae, benthic fishes and pelagic fishes. Based on these correlations, many have concluded that climatic forcing has a strong influence on populations and assemblages. Pattern seeking of this type requires data sets that encompass long periods if they are to relate with a wide range of climatic conditions (eg El Niño to La Niña). Data sets of greater that 10 years have shown strong relationships between climatic indices and recruitment.

Attrill and Power[4] concluded that climatic forcing (over 16 years, North Atlantic Oscillation) was consistently the most important parameter explaining variation in assemblage composition, abundance and growth of juvenile marine fishes during estuarine residency. The recruitment of West Australian rock lobsters correlates strongly with the Southern Oscillation Index, where recruitment is highest in La Niña conditions (over 18 years[19]). Interestingly, direction of correlations varies according to taxa. For example, Caputi et al.[19] found a negative correlation between the Southern Oscillation Index and recruitment of lobsters while there was positive relationship for bivalves. Parrish and MacCall (in Sissenwine[124]) could explain 60 to 86 percent of the variation in recruitment of Pacific mackerel to a survival index. Empirical models do not explain the processes influencing recruitment, but provide a hypothesis-generating platform for further investigation. Furthermore, robust models can be used to make accurate predictions of levels of recruitment to populations or movement that includes important commercial stocks[86]. Parrish and MacCall[104] argued that 84 percent of their survival index was due to zonal Ekman transport. This oceanography transports larvae from offshore spawning grounds to inshore nursery areas.

Empirical models are not causal since the physical variable is only a proxy for an underlying biological process. For example, the Southern Oscillation Index may correlate with current flow that influences the transport of larvae, or correlations of abundance with increased temperature may be indicative of good feeding conditions.

Table 18.4 presents information on the sensitivity, potential impact, adaptive capacity, and linkages and interactions that may result from exposure to multiple climatic factors. Stressors with greatest potential for impact are sea temperature and nutrient enrichment, followed by oceanography and sea level rise. Some of these stressors are not independent, for example, oceanography can alter patterns of sea temperature and nutrient enrichment. Changes in water chemistry have the potential for far reaching change. However, this is more likely at time scales beyond 50 years from present.

## 18.5.4 Oceanography

### 18.5.4.1 Exposure and sensitivity

All organisms that are dependent on pelagic food resources and the pelagic environment for larval transport will be exposed. Predictions are for only minimal changes in current direction and changes in current strength. However, some change to the oceanography of the GBR would be expected as a result of sea level rise that will influence local currents.

### 18.5.4.2 Potential and observed impacts

Changes in current direction and speed could alter patterns of connectivity and the ability of larvae to return to natal (ie source) reefs. For example, Cowen et al.[23] found that the return of larvae to a reef was dependent on depth stratified currents, where deep currents advected larvae onshore. Expatriation of larvae through adverse currents could have a large influence on populations[59]. Changes in currents could also influence the movement of pelagic larvae from spawning grounds to recruitment areas. The position of retention areas could change, influencing not only plankton but also the nekton that depend on them (eg bait fishes and predators).

### 18.5.4.3 Adaptive capacity

Unknown for plankton, but there is the potential for larvae to alter patterns of vertical migration in response to changes in currents. Large nekton may alter patterns of migration and patterns of biomass[86].

### 18.5.4.4 Vulnerability and thresholds

All taxa are vulnerable, but changes in currents are predicted to be small with some changes to currents nearshore due to sea level rise being the most significant. The interaction between currents and patches of different temperature water is likely to have the greatest effect on pelagic organisms and cause the greatest vulnerability.

## 18.5.5 Sea level rise

### 18.5.5.1 Exposure and sensitivity

Although the projected sea level rise is unlikely to cause great change over the continental shelf at mid and outer distances, there would be effects nearshore due to changed nutrient and sediment regimes and changes in size of estuarine and mangrove forest recruitment areas. Local sea levels will vary according to topographic channelling of tidal waters to adjacent basins (eg near Cairns sea level rise is not expected to be as great as two metres; J Nott pers comm). A catastrophic increase in sea level due to the melting of major ice caps may be too fast a change for nearshore production cycles to re-establish. Populations with restricted depth tolerances may struggle for physiological reasons or due to an inability to interact with organisms from other depths (ie competition and predation). A two to ten metre sea level rise will alter local currents for local populations with subsequent oceanographic influences.

### *18.5.5.2 Potential and observed impacts*

There are likely to be changes in the size and quality of nursery areas that are critical to the recruits of many fishes and invertebrates. Some shallow water habitats would increase, as predicted for mangrove habitat on the mainland, while others may disappear due to steep sided islands, similar geomorphology and landward constraints by man made structures (Lovelock and Ellison chapter 9). Many changes due to sea level are likely to affect benthic rather than pelagic organisms, but most marine organisms have pelagic larvae and the composition of pelagic larval assemblages would change if intertidal assemblages changed greatly as a result of sea level rise. Sediment regimes may change and local levels of production (eg from detrital food chains) may alter and affect interactions with pelagic organisms. There is also the possibility that increased inundation of land will increase the input of pollutants to inshore waters of the GBR. The latter scenario may not be significant as the size of populated areas adjacent to the GBR is relatively small (ie there are only three cities with populations greater than 100,000). The inundation of beaches used by turtles for nesting may alter patterns of reproduction on the GBR and therefore that component of the pelagic environment.

### *18.5.5.3 Adaptive capacity*

Some pelagic organisms may migrate away from areas that have been inundated or altered by sea level rise, and in some cases there may be local extinctions where water depth becomes too great. If the inundation of coastal habitats is slow then critical coastal and estuarine habitats should re-establish as they have done in the past (eg mangroves[144]). However, a sudden sea level rise due to the melting of polar ice caps would allow less time for relatively gradual changes of habitats.

### *18.5.5.4 Vulnerability and thresholds*

Nearshore assemblages will be most vulnerable to changes in sea level, with the areas of greatest concern being nursery areas. There is an unknown component of vulnerability to sea level rise due to the possible melting of polar ice caps and a sudden sea level rise.

## 18.5.6 Sea temperature

### *18.5.6.1 Exposure and sensitivity*

Plankton and nekton of the pelagic environment in the GBR will be highly exposed to the 1 to 3°C increase in mean sea temperature predicted. Temperature anomalies will be experienced as patches of warm water that remain in an area for a short (pulse) or long (press) time. Although warm water is low density and should float, a high level of mixing on the shelf would be facilitated through physical processes such as wind, tide and currents, so temperature incursions may be experienced at all depths.

### *18.5.6.2 Potential and observed impacts*

Many pelagic organisms have the capacity for substantial vertical and horizontal migrations through the water column and this could encompass temperature ranges of greater than 3°C. It could be predicted, therefore, that the potential impact on pelagic organisms due to temperature increases in the next 100 years will be slight. However, for most organisms there are no data on response to upper critical levels of temperature (ie thermal tolerance above a temperature such as 31°C). Temperature tolerance may cause mortality but critically there may be sub-lethal effects on larvae and other plankton such as changes to growth, vulnerability to starvation and predation, behaviour and longevity[75]. Shifts in the structure of prey and predator communities is likely to be a major secondary effect on many plankters within the pelagic plankton as has been documented at other latitudes and this is likely to affect the growth, development and survival of larvae[6].

Higher water temperatures can improve growth rates in larvae of *Pomacentrus coelestis* on the tropical northwest coast of Western Australia[94]. Sponaugle et al.[127] found this was the case also for the tropical wrasse *Thalassoma bifasciatum*, and that recruitment was higher, although more variable, in warmer water conditions. Squid also grow faster in warmer water[33].

For nekton, variation in sea temperature is likely to change movements, particularly if prey are affected. There are demonstrated temperature limits that influence the distribution and abundance of the bait fish round sardinella (*Sardinella aurita*) in the Mediterranean Sea[119]. The movement of bait fish can also affect the movements and survival of fishes and birds that feed on them (Congdon et al. chapter 14).

Changes in planktonic assemblages have been demonstrated to vary with sea temperature. For example, warming in the north Atlantic has affected the composition of plankton[115] and the feeding environment for larval cod that are now thought to have poorer conditions for feeding[6]. It is also thought that the frequency of harmful toxic algae blooms that can affect nekton will increase[30]. In addition, warmer waters are likely to change the timing of phytoplankton and zooplankton blooms and influence the larval and older forms that are dependent on them[29]. Zeldis et al.[152] argued that salp outbreaks were more common in warm water and the feeding activity of the salps destroyed a suitable feeding environment for fish larvae[153]. Slight increases in water temperature have been shown to alter the balance between plankton autotrophic and heterotrophic communities in temperate environments[100,126].

Sea temperature has the potential to affect nekton. On Australia's east coast, Hobday[55] predicted that under the various IPCC assessment scenarios of climate change, the range of southern bluefin tuna (*Thunnus maccoyii*) would contract southwards, while yellowfin tuna (*Thunnus albacares*) will increase their distribution and abundance. Demographic changes have been noted in a number of North Sea fish species with altered distributions in response to recent changes in water temperature. Further, it is species with shorter life cycles that have shown the greatest response[107].

Humpback whales annually migrate to mid-GBR waters during the cooler winter months to give birth to calves. It is possible that with increases in temperature these migrations will contract further south (Lawler et al. chapter 16).

Increased ocean warming is likely to alter spatial distribution of primary and secondary pelagic production in the pelagic environment, with a cascade effect up the food chain, potentially placing greater stress on fish and mammal populations[115] (Lawler et al. chapter 16). Predicting the responses of pelagic communities to increasing water temperature is difficult given the complexities associated with the inter-relationships of different trophic levels and the multitude of different species within these levels.

### 18.5.6.3 Adaptive capacity

The ability of larval, juvenile and adult forms to alter thermal tolerances is poorly known. Lamnid sharks (eg mako and white sharks) are able to regulate their body temperature and so are more adapted to occupy a greater range of environmental temperature regimes (Chin and Kyne chapter 13). However, these species are infrequent GBR visitors. Lamnids and pelagic tunas and billfish are unique in that they can essentially regulate their body temperature via an internal countercurrent system and a structure called a *rete mirabile*. This essentially means that they have higher body temperatures and provides the ability for niche expansion[41]. These species are naturally suited to adapt to changes in sea temperature. Mobility is important for nekton, but changes in prey distribution may be more influential.

### 18.5.6.4 Vulnerability and thresholds

Planktonic organisms are highly vulnerable to environmental changes, which can result in a trophic cascade as observed in the northern hemisphere. In the medium term on the GBR this is likely to be restricted to sections of the GBR that are exposed to press events of warm water. Temperature thresholds are poorly known for tropical plankton and nekton. Nekton can move in response to changes in temperature but they may experience recruitment failure of larval habitat and juvenile nursery grounds may be compromised.

## 18.5.7 Ocean chemistry

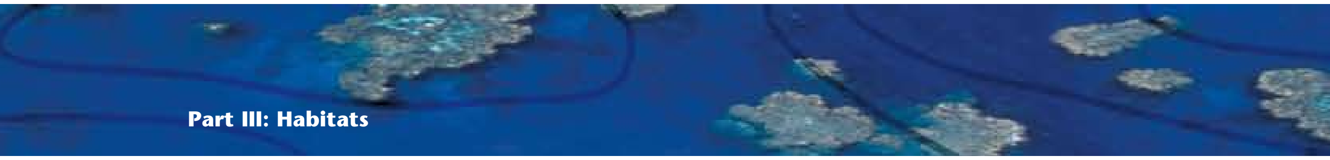
### 18.5.7.1 Exposure and sensitivity

Climate change projections predict increased dissolved $CO_2$ accompanied by a reduction in the oceanic pH of 0.5 units by 2100 (Lough chapter 2). Calcifying zooplankton will be most susceptible to this change[102], but intracellular and physiological affects (eg changes in respiratory efficiency, growth and reproduction) are also likely to occur[114]. Pelagic eggs and larvae of fish and invertebrates will be exposed to these changes and are likely to be highly sensitive to them. It is unknown how local buffering effects of calcium carbonate reefs will affect the pelagic environment of the GBR.

If a rate of change of 0.5 units over 100 years is realised it will be the fastest rate of change experienced by marine organisms for about 400,000 years[114]. However, marine organisms have had to deal with ocean $CO_2$ concentrations that were three to four times higher than present about 100 million years ago (Cretaceous era[11]) and pH would have also been lower. However, many organisms that are critical in pelagic food chains today have a form of calcium carbonate in their skeletons called aragonite that is more susceptible to changes in pH than calcite, which was more abundant in the skeletons of organisms 100 million years before present. Not withstanding unknown buffering effects due to calcium carbonate stored in the dead matrix of coral reefs, organisms will have to deal with lower pH over time.

### 18.5.7.2 Potential and observed impacts

Adult pelagic species are likely to be less sensitive to predicted changes in ocean chemistry than early life history stages although few data are available. It is likely that selective removal or reduction in abundance of some taxa will result in trophic cascade effects with potential negative impacts on the



pelagic food chain. Potential decreases in abundance of particular zooplankton, particularly calcifying species[117], will lower food reserves for planktonic larval species possibly lowering recruitment levels. Carbon flux to the substratum, through marine snow, would alter due to increases in polysaccharide production. The production of these complex sugars would increase with higher photosynthetic rates of phytoplankton cells, a response to increased levels of $CO_2$[31]. Changes in benthic assemblages can also link with pelagic ecosystems. For example, many molluscs have a critical role in releasing nutrients from sediments. If the mortality, growth and reproduction of these organisms are affected then nutrient exchange with the water column may be altered and this could in turn facilitate a trophic cascade. If coral reefs are compromised by reduced pH then this could change the habitats of many organisms that interact with and contribute to the pelagic environment through feeding and reproduction[40]. The oceans are critical in the global carbon cycle and changes in the ability of the ocean to absorb $CO_2$ could affect rates of global warming[114].

### *18.5.7.3 Adaptive capacity*

Given that ocean chemistry has been historically highly stable, it is unknown how pelagic organisms will respond to changes in ocean $CO_2$ concentrations and pH. Generation times of phytoplankton and zooplankton can be rapid suggesting good adaptive capacity for organisms such as copepods. The capacity of different organisms to respond to change is likely to be highly variable and is difficult to predict. Most experiments that have been done on tolerance to variation in pH are too short term (ie responding to pulse not press impacts) to be relevant[114].

### *18.5.7.4 Vulnerability and thresholds*

Organisms in the plankton, including larval forms and crustacean stages, are likely to be the most vulnerable in the pelagic environment. Thresholds for tropical plankton species are poorly known and are likely to be highly variable across the myriad of species present.

## 18.5.8 Ultraviolet radiation

### *18.5.8.1 Exposure and sensitivity*

Ultraviolet radiation levels on the GBR are not predicted to change significantly. Therefore, although many pelagic organisms occupy the upper 20 to 30 metres of the water column, they are not likely to be exposed to changes in UV radiation. Phytoplankton are known to be sensitive to increases in UVB exposure.

### *18.5.8.2 Potential and observed impacts*

Should current predictions of UV radiation levels alter, a reduction in phytoplankton levels is possible which would result in changes in species abundance and composition at higher trophic levels. Zooplankton community composition may also be altered.

### *18.5.8.3 Adaptive capacity*

Although it is known that some phytoplankton species can respond quickly to changes in UV exposure, few studies exist for tropical species (McKinnon et al. chapter 6).

#### *18.5.8.4 Vulnerability and thresholds*

Based on current predictions the pelagic environment is not considered to encounter changed UV radiation conditions over the next 100 years.

### 18.5.9 Rainfall, nutrient enrichment and cyclones

#### *18.5.9.1 Exposure and sensitivity*

Predictions of changes in rainfall and cyclones on the GBR are uncertain. However, it is predicted that although there may be no change in their frequency, the intensity of extreme events will increase. This will expose the pelagic environment of inshore areas to more intense events of increased nutrients associated with flood plumes. Exposure may also extend further offshore (depending on currents and wind) to mid- and offshore reefs where few flood events have been experienced in the past. This may mean that organisms further offshore are more sensitive than their inshore counterparts. More intense winds from cyclones would exacerbate the enrichment of pelagic waters through mixing of benthic layers with surface waters. Increased flooding will also reduce salinity and temperature. Changes in sea level may also cause changes in nutrient enrichment depending on how drainage systems change with increased inundation.

#### *18.5.9.2 Potential and observed impacts*

It is uncertain how ENSO events will alter in the face of climate change, if at all, so changes in upwelling and down-welling events on the GBR are unknown. An increase in nutrients would generate bottom-up responses of the pelagic food chain[134] and significant changes in planktonic assemblages would be expected. Impacts of high nutrient inputs to the GBR are likely to be greatest in inshore areas, however there will also be increased occurrence of nutrient rich flood waters on mid- and outer-shelf reefs. Recruitment of fish and crustacean species is likely to be enhanced and will possibly result in much higher inter-annual variability in recruitment of populations. This may have significant impacts on fisheries production but may also alter biological and fishery stability. Changes in nutrient regimes also have the potential to alter the recruitment of gelatinous zooplankton including dangerous cubozoans. Aside from increased risk to the public, abundant gelatinous zooplankton has the potential for top-down effects where other plankton proliferates, including those that can generate toxic blooms[32,30].

Cyclone events are likely to have more localised effects. Increased flood events and associated winds may also have lethal or sub lethal effects on organisms sensitive to low salinity or benthic organisms sensitive to turbid conditions and increased sedimentation. Increased intensity of rainfall, cyclones and nutrient enrichment is likely to result in a more variable ecosystem and impacts may vary spatially within the GBR.

#### *18.5.9.3 Adaptive capacity*

In response to rapid changes associated with storm and rainfall events, some organisms can move away if conditions become unfavourable. Benthic organisms will be less capable of responding to these events.

### *18.5.9.4 Vulnerability and thresholds*

Changes in nutrient levels will cause fundamental changes in pelagic assemblages. The composition of plankton changes quickly in response to changes in nutrient levels and this will in turn affect nekton. Experimental perturbations demonstrate rapid change. In Kaneohe Bay, Hawaii, for example, nutrient enrichment occurred from sewage that was pumped into the bay from the 1950s to 1977. The major uptake of inorganic nitrogen and phosphorus was by phytoplankton and this supported abundant zooplankton. When the sewage was diverted, biomass of plankton decreased rapidly[125]. As with other stressors, plankton in the pelagic environment will therefore be most vulnerable to changes in nutrients. However, this will result in community changes at higher trophic levels as they respond to altered primary and secondary production as well as changes in species assemblages in the plankton. Some benthic organisms may be most vulnerable to these rapid changes.

## 18.6 Linkages, interactions and implications

It is clear that changes to pelagic ecosystems will result in trophic cascades from plankton to benthic assemblages. The supply of planktonic food affects invertebrates and fish alike. Suspension feeders depend on plankton and changes in plankton supply from currents, upwelling, riverine input and other sources will affect them.

Excess plankton (eg algal blooms) can result in deoxygenated waters and death of benthic organisms. This has happened with prolonged El Niño conditions and atypical temperatures in New Zealand where diatom blooms were generated and then collapsed to decompose near the substratum, killing invertebrates and fishes[129].

Most benthic algae, fishes and invertebrates have a pelagic phase to their life history. Algae have spores and marine animals generally have pelagic larvae and often pelagic eggs. Conditions in the water column, therefore, will affect the probability of survival of these organisms (Table 18.3). It will also affect connectivity and the ability of pelagic organisms to be transported or move between environments and detect suitable habitat for successful settlement and growth[37].

The pelagic habitat of the GBR links with open ocean systems through pelagic fishes and marine mammals that visit the GBR on occasion or have strong seasonal migrations[68]. The nature of these links will vary according to environmental variation such as sea temperature, which can be used as a proxy for good feeding conditions[86]. On the GBR, there are geographically stable aggregations of bait fish (section 18.3.4) that attract open water predators and act as Effective Juvenile Habitat for pelagic fish such as marlin. The climatic factors that affect the fidelity and size of these aggregations will have a great effect on the local pelagic food chain.

Variation in pelagic stressors will affect the whole food chain, and this was dramatically observed in Peru where an upwelling failure resulted in altered bait fish distribution, lower survival of fish larvae, the movement of large nekton such as tuna, whales and sharks away from the area and the starvation of birds and other animals that depend on bait fish. Fisheries and the communities that depend on them are also greatly affected when these events occur[54]. There is varying certainty about how climatic factors will vary in the GBR in the short and long term. Variation in sea temperature and

sea level are the most certain along with long-term changes in pH. Changes in nutrient enrichment and oceanography will occur at local scales. All of these stressors will affect biota at different spatial and temporal scales, will interact with each other and therefore require multiple approaches by environmental managers.

## 18.7 Implications for management and recommendations

The implications that come from this review are as follows:

i) Predictions of global change and related environmental stressors are often weak, especially at spatial scales of less than one hundred kilometres.

ii) Changes in environmental stressors will alter the pelagic environment and linkages with other environments (eg coral reefs).

iii) Pelagic systems are quickly influenced by bottom-up (eg nutrient input) and top-down processes (eg predation) while mobile nekton can move great distances in response to environmental change.

iv) Predictions of physical change suggest that within the next 50 years biological changes in pelagic systems are likely to occur in patches on the GBR, rather than the entire region. Managers will have to deal with impacts on scales of tens to hundreds of kilometres in the medium term and spatial scales of impact are likely to increase with time.

Our recommendations to managers are:

i) Reducing $CO_2$ emissions to the atmosphere is the only practical way to minimize the risk of large-scale and long-term changes to the oceans[114].

ii) Managers need to set up relevant monitoring programs and research taking into account regional variation in GBR physical and biological processes.

iii) Monitoring of pelagic and benthic assemblages provides early warning of change. Coral reefs are considered the canaries in the coalmine, but plankton are the silent sentinels of change, as demonstrated in the northern hemisphere[6].

iv) Monitoring changes in physical oceanography can also warn of potential change. A GBR network of sensors and satellite imagery would allow broad scale monitoring of physical changes in currents, water temperature, salinity, pH and upwelling. It is critical that climatic conditions on the GBR are monitored. It is also important that predictions and measurements are made of patches of water with a high stress rating (eg waters over 31°C) and the time they spend in an area (ie pulse or press).

v) Monitoring catches of key taxa such as bait fish and large piscivores will track changes in pelagic fish assemblages, which has proven useful in the northern hemisphere.

vi) Patterns of growth, movement, reproduction and biogeography of many taxa track the environment and should be researched and monitored.

vii) Monitoring of plankton is time consuming and research on plankton should be used to develop models that predict biological responses to changes in environmental stressors.

viii) Some changes in the environment may increase risk to the public through toxic blooms and dangerous jellyfishes. Monitoring of these groups would be judicious as would the development of predictive models.

ix) Few data are available to managers on the response of different organisms to stressors. Field and laboratory-based research is required to determine the impact of pulse and press type perturbations on organisms. Early life history stages are the raw material of marine populations and are likely to be most vulnerable[75]. Responses to stressors can be lethal or sublethal as well as acute or chronic and the literature on pollution provides a useful framework for this type of research (eg Underwood and Peterson[132]).

x) Marine Protected Areas (MPAs) and fisheries management don't protect against the impacts of climate change, but will reduce additional stress on habitats and organisms not attributable to climate change[8]. Current management of the GBR through MPAs and fisheries management are considered excellent by international standards, but protection of pelagic taxa is more challenging. One option, however, would be to have increased protection of bait fish where they regularly concentrate. Protected areas could include Effective Juvenile Habitats in coastal bays, which are critical for many game fish, as well as areas of upwelling.

xi) Pelagic 'predator diversity hotspots'[147] may be protected. The protection of diversity may allow ecosystems to recover from perturbations as the loss of diversity can impair normal ecosystems function[149].

With climate change and related variations in environmental stressors it is inevitable that there will be changes in the biogeography of benthic and pelagic organisms. Species replacements are possible, as recorded through times of historical environmental change, and fisheries managers of the GBR will need to monitor target taxa and review quotas. There is an element of wait and see, but vigilance and increased understanding of the response of organisms to stressors are the keys to considering options for adaptive management.

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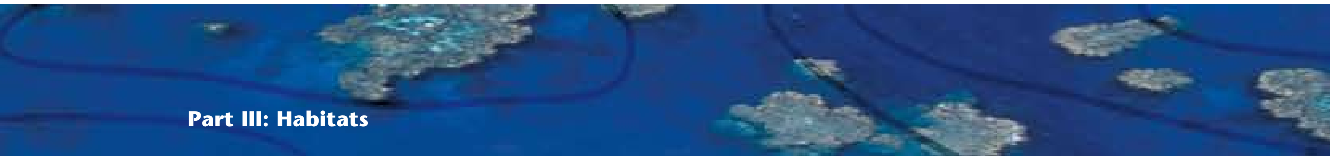

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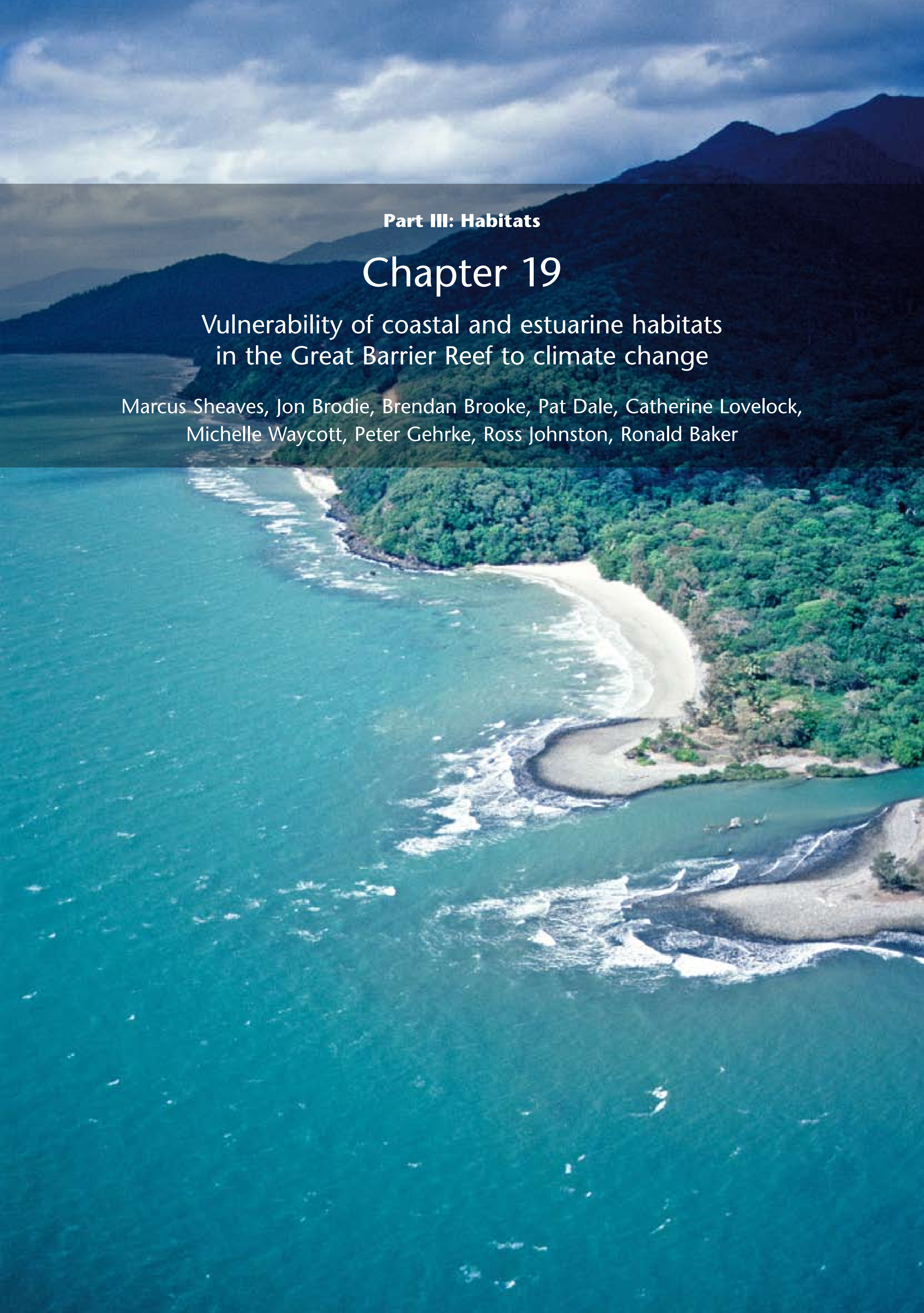
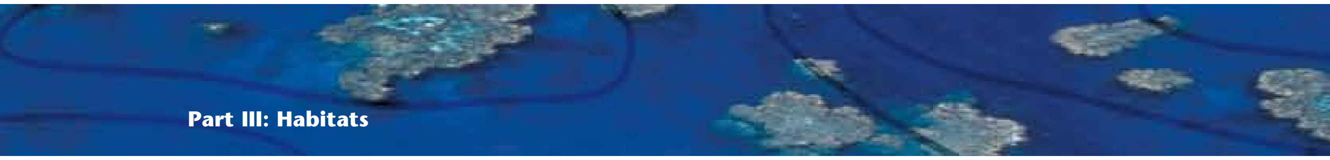


Part III: Habitats

# Chapter 19

## Vulnerability of coastal and estuarine habitats in the Great Barrier Reef to climate change

Marcus Sheaves, Jon Brodie, Brendan Brooke, Pat Dale, Catherine Lovelock, Michelle Waycott, Peter Gehrke, Ross Johnston, Ronald Baker



## 19.1 Introduction

Coastal and estuarine habitats occupy a central place in the functioning of tropical marine ecosystems. Their location at the interface between land and sea means they function to modulate the movement of terrestrial materials (eg freshwater, nutrients and pollutants) into the marine environment[160]. Coastal and estuarine habitats also act as a filter, with functional units such as mangrove forests inhibiting trapping and retaining sediments and nutrients[157]. Coastal habitats are also crucial nursery grounds for many species of fish[111] and crustaceans[152], and act as links in the life cycles of species that migrate between marine and freshwater habitats[134]. Beyond this, their close proximity to population and industrial centres makes them the marine habitats most vulnerable to human impacts.

The east coast of tropical Queensland comprises a diversity of habitats, ranging from freshwater and littoral marshes, through estuaries, to nearshore open oceans and reefs. These habitats do not function alone but are an interlinked coastal ecosystem mosaic (CEM), connected at a variety of spatial, temporal, functional and conceptual scales[51]. This complex mix of habitats is inhabited by one of the most diverse faunas on earth[60] with organisms covering the full taxonomic spectrum, from viruses and bacteria to cetaceans. Unfortunately, detailed ecological knowledge is limited to a very small subset of the range of these organisms, with many species unknown, unidentified or unquantified[60,33]. Although it is clear species interact in complex ways, our understanding of this is critically deficient. Moreover, many of the individual components are poorly understood, and details of the links between them largely absent.

This chapter attempts to address the vulnerability of the CEM in the Great Barrier Reef region to global climate change. It does not consider individual habitats (eg reefs or seagrasses) but goes beyond the individual species and habitat assessments, to consider impacts on the whole coastal marine community complex, and the ecological processes that support its functioning.

Due to the diversity of organisms and habitats[60,8], the variety of physical processes involved[165], and their intricate interlacing[93], impacts of global climate change are likely to be complex, pervasive and difficult to predict. Additionally, there are likely to be emergent impacts on ecological processes above and beyond those related to, or predictable from our knowledge of individual taxa or individual habitat and ecosystem components. Unfortunately, at present there is sparse understanding of even the best-researched components on which to base an authoritative vulnerability assessment. Consequently, the major message of this chapter is that more targeted information is needed to make a comprehensive evaluation of the likely impacts of climate change on coastal systems. Although, this chapter addresses the whole CEM, in reality there is little understanding of most of the components of this complex outside of estuaries. Consequently, by necessity much of the discussion will focus on estuaries, and even this discussion draws heavily on understanding from outside of the tropics.

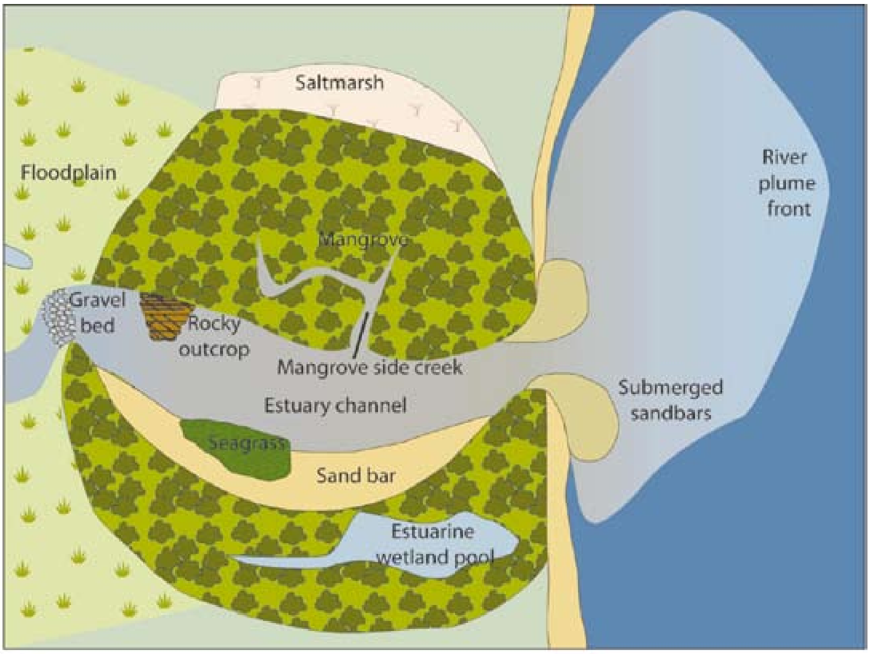
### 19.1.1 The nature of the coastal ecosystem mosaic

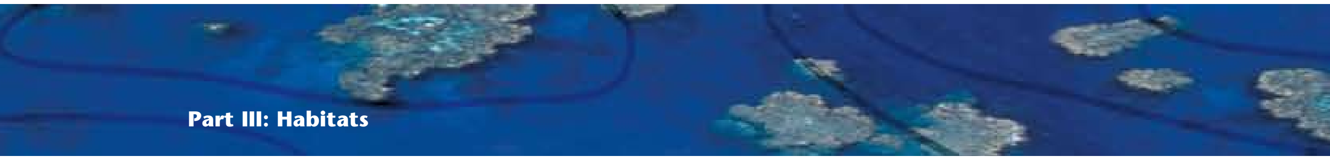
Even at the coarsest level of resolution the diversity of habitats comprising the CEM is obvious (Figure 19.1). Nearshore open ocean, coastal reefs and rocky headlands, beaches, river plumes, estuaries, mangrove forests, salt marshes, estuarine and freshwater wetlands, and freshwater streams are linked by their proximity, the physical transport of material, the movements of organisms, and a variety of physical and ecological processes. Although this resolution is coarse it is still difficult to unambiguously disentangle habitats at different scales[134], with a complete habitat from one point of view being an ecosystem component from another point of view.

Within ecosystems are a range of habitats that occur in various combinations. For example, estuaries (defined as areas where sea water and freshwater mix) comprise a variety of vegetated and non-vegetated habitats (Figure 19.1). Some of these components are peculiar to estuaries, others occur in combination with other habitat types in other parts of the CEM. At this scale there are many components (eg mangrove and seagrass) that are treated in detail in other chapters.

Although the components of CEM are a heterogeneous group, with a variety of properties (eg differing in depth, structure and complexity), they are linked by both the physical movement of materials (physical connectivity), and by the movement and interdependence of organisms and communities[93,51]. Physical connectivity can be seen in the outflow (and inflow) of sediments, nutrients and pollutants through the CEM[162,48,158]. Biological interdependence is obvious in the lack of concordance between the distributions of many organisms and the scale and extent of identifiable habitat or ecosystem units[51] Life history migrations (eg to access nursery grounds)[111,112,131], and shorter-term movements (eg feeding forays)[133], increase this interdependence by linking the mosaic within the lives of organisms and transferring nutrients and energy between various components of the mosaic. This biological connectivity links the components at a diversity of spatial and temporal scales.

***Figure 19.1*** *The habitats that make up the Coastal Ecosystem Mosaic that comprise coastal and estuarine habitats of the GBR region*





## 19.2 Exposure and sensitivity to climate change

Due to the complexity of the CEM there are many physical, biological and functional aspects, varying substantially in focus and scale, that are likely to be impacted by global climate change (Table 19.1).

Climate interacts with other physical processes to produce surface characteristics such as topography, soils and water (both surface and subsurface), and to determine the nature of an area's physical environment. This interaction means physical processes are likely to be impacted by most aspects of climate change. The diverse and complex biological processes active in the CEM (Table 19.1) are set within this physical framework. Consequently, their exact natures and the integrity of their functions are closely tied to the environment, meaning climate change has the potential to lead to profound changes. These biological processes are often complex involving a diversity of organisms (eg trophic function) and impinge on every aspect of life. As a result, change to any one component is likely to have far reaching effects, and these effects are likely to be transmitted, and often amplified, throughout the linkages of the CEM. Beyond this, coastal marine habitats fulfil a variety of ecosystem services such as flood control, pollution filtration, nutrient recycling, sediment accretion, groundwater recharge and water supply, erosion control, and plant and wildlife preservation[57]. These pivotal roles mean that climate change is likely to have far-reaching effects that go beyond direct and indirect impacts on biota.

***Table 19.1*** *Summary of features and processes likely to be influenced by climate change*

| Feature or process | Climate change process with greatest potential impact | Aspects likely to change |
|---|---|---|
| Physical processes relevant to ecosystems | sea level change<br>rainfall patterns<br>severe weather events<br>acidification<br>temperature | coastal/estuarine geomorphology<br>estuarine flushing<br>sediment loads<br>nutrient transport<br>salinity profiles<br>ecosystem-specific chemistry |
| Habitats and ecosystems | sea level change<br>rainfall patterns<br>severe weather events<br>temperature | extent of particular habitats/ecosystem components<br>relative proportions of habitats<br>habitat interspersion, patch size, pattern, connectivity<br>habitat boundaries<br>habitat availability |
| Species and species-level ecological functions | sea level change<br>rainfall patterns<br>severe weather events<br>acidification<br>secondary outcomes from effects on habitats and species<br>temperature | abundance<br>distribution<br>spawning<br>supply of recruits or propagules<br>temporal and spatial matching with prey/ nutrients |

| Feature or process | Climate change process with greatest potential impact | Aspects likely to change |
|---|---|---|
| Trophic function | secondary outcomes from effects on habitats, species and diversity | food web structure and integrity<br>physically mediated nutrient flows<br>biologically mediated nutrient transfers<br>balance of export/import<br>dominant trophic processes |
| Connectivity | sea level change<br>rainfall patterns<br>severe weather events<br>secondary outcomes from effects on habitats and species | physical connectivity<br>biological connectivity<br>overall ecosystem linkages |
| Higher level ecological functions | temperature<br>sea level change<br>rainfall patterns<br>severe weather events<br>acidification<br>secondary outcomes from effects on habitats, species and diversity | nursery ground function<br>ecosystem/habitat dependence<br>regularity/periodicity of ecosystem structuring events (eg cyclones)<br>changes in complex ecosystem interactions<br>changes in structure of production models<br>impacts on key ecosystem components<br>fisheries production |
| Diversity | temperature<br>sea level change<br>rainfall patterns<br>severe weather events<br>acidification | taxonomic diversity<br>functional diversity |
| Interactions with anthropogenic factors | sea level change<br>rainfall patterns<br>severe weather events<br>acidification<br>secondary outcomes from effects on habitats, species and diversity | interactions with anthropogenic stressors<br>interactions with human response to climate change |

## 19.3 Vulnerability to climate change

A common theme of the previous individual species and habitat chapters is a general uncertainty about the details, magnitude and even the direction of effects of global climate change. These uncertainties are magnified when extrapolated to the scales of individual habitats, the CEM and high-level ecological functions.

### 19.3.1 Physical processes

The Great Barrier Reef (GBR) coast comprises 42 percent sandy beaches, 39 percent muddy shoreline and 19 percent rocky exposures[49]. Each type of coast has distinctive assemblages of habitats and types of vulnerability to climate change. The nature of any climate-induced change is likely to be region specific[163]. In general terms, sandy coasts are susceptible to recession and erosion due to sea level rise and increased frequency of storms[75]. Habitats associated with muddy coasts (eg mangroves and salt marsh) and adjacent low-lying freshwater swamps are vulnerable to shoreline erosion, the landward incursion of saltwater and changes in rainfall (eg Nicholls et al.[92], Rogers et al.[114]). Rocky coasts are less prone to erosion, depending on rock type, than the sedimentary coasts. However, associated marine biota, such as intertidal attaching organisms, will likewise be affected by changes in sea level and wave exposure associated with climate change.

The particular spatial pattern of physical environments found on the GBR influence the extent to which various components of the CEM are vulnerable to climate change. Although the coast is largely protected from ocean swell by the outer reefs, there is significant variability in the local and regional sea surface temperature, wind, wave and tidal regimes. For example, large tides on the central and southern coast are a major control on coastal processes, and sea surface temperatures are significantly lower in the southern GBR (mean annual range 22 to 27°C) compared to the north (mean annual range 25 to 29°C[80]). The coast is also characterised by strong gradients in rainfall, with a marked decline in the average annual rainfall from Cairns (3200 mm) towards both the far northern (1600 mm) and southern (1000 mm) margins of the GBR coasta. Similarly, the frequency of cyclones declines to the south from approximately 0.4 cyclones per year on the Cape York coast (30 year annual average) to 0.1 at the southern margin of the GBR[a][85]. The set of climatic and oceanographic conditions each region experiences results in a distinctive set of landforms and geomorphic processes. For example, estuary type ranges from river-dominated deltas in the wetter areas, with relatively low tidal and wave energy, to tide-dominated estuaries on the drier, macro-tidal coasts[61].

Changes in climate, and particularly in sea level, at a rate greater than that previously experienced over geological time[52], will cause far-reaching impacts on processes of erosion and sedimentation. An increased incidence of extreme events may lead to acute episodes of high erosion in upper catchments and then to high rates of deposition in CEM areas. Rates of sedimentation are critically important in determining responses to sea level change. Additionally, if erosion increases in the CEM then there will be a high risk of acidification as much of the coastal area below 10 metres Astronomical High Datum is underlain by acid sulphate soils[31]. Oxidation occurs when acid sulphate soils are exposed to air and subsequent wetting leads to runoff of sulphuric acid. This is highly detrimental to organisms because acid can mobilise aluminium and cause death of fish and other organisms, or render them susceptible to disease[143,122]. Effects of estuarine acidification can impact all trophic levels resulting in both short- and long-term damage[121].

Of all the possible impacts of climate change, variation in rainfall patterns is likely to have the most far-reaching influences on estuarine ecology because freshwater flow is generally the largest source of physical variability in estuaries[139,68]. Variation in freshwater inflow determines inundation of floodplains and supra-littoral habitats, nutrient loadings, advective transport of materials and organisms,

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[a] Bureau of Meteorology 2006, Climate averages: http://www.bom.gov.au/ climate/ averages/

the location, intensity and nature of estuarine salinity profiles and density gradients[68]. It also affects community structure, faunal distribution[157] and community function[139]. In fact, changes in the severity and periodicity of episodic events are, in themselves, a problem because these are part of the normal cycle that maintains estuarine productivity[160].

Changes in the timing, magnitude and variability of rainfall influence five fundamental characteristics of inflow to estuaries[108]: i) the *magnitude* of conditions (eg salinity, depth and available habitat area), ii) the *timing* of occurrence of conditions, iii) the *frequency* of occurrence of conditions, iv) the *duration* of conditions and v) the *rate* of change of conditions. The extent to which environmental needs, and life-history needs and timings, match with this combination of factors determines the ability of organisms to continue to use and thrive in estuarine habitats[108]. In turn these influences flow-on to affect other dependent organisms and processes. Importantly, such effects are often complex and indirect[97], and impose their influences across a spectrum of time scales, with effects often lagged by a year or more[24].

As well as direct consequences for ecological functioning, freshwater flows influence other factors, such as salinity, temperature, turbidity, dissolved oxygen and nutrient supply, which in turn impact ecological functioning[132,105]. For example, changes in the rate and timing of freshwater inflow can cause shifts in water quality parameters in estuaries, bays and tidal marshes that ultimately affect distributions of fauna[64,128]. In fact, changes in inflow can completely alter the nature of an estuary, with ‘reverse estuaries’ developing, where salinity increases upstream[98], as a response to high evaporation coupled with low freshwater inflow[88], or shorter hydroperiods[79]. Such effects are likely to be particularly severe in dry tropics estuaries where hypersaline conditions develop rapidly following the end of the wet season[109]. In some locations the estuary becomes a fully reverse estuary, that is, the salinity increases monotonically from the mouth to the head. In other locations, a salinity maximum zone separates the sea from low salinity water that persists at the head of the estuary throughout the dry season[109]. Even under present conditions freshwater flows can be reduced to insignificant levels for periods of five years or more[135].

Coupled with other influences of global climate change, the effects of changes in the pattern of freshwater inflow to estuaries on salinity, temperature, sediment delivery and movement and nutrient supply has far reaching ecological implications. These implications extend to communities and ecosystems, the distribution, abundance and diversity of plants and animals, migration and nursery ground function, habitats and habitat availability, primary production, nutrient cycling and food webs, overall estuarine health, and the resilience of estuarine habitats to human impacts. Moreover, these effects are likely to have interactive, and not necessarily linear or simple additive effects.

Despite the range of likely detrimental effects, physical change in itself is not necessarily bad. Physical instability (eg flow variation) is important in maintaining stable biological functioning of estuaries[78]. In reality, a major danger in climate change is that the normal cycle of variability will be disrupted, modifying the periodicity and extent of the ‘resetting’ of estuaries by episodic events that are essential in maintaining estuarine productivity, trophic structure and habitat diversity[160].

### 19.3.2 Habitats and ecosystems

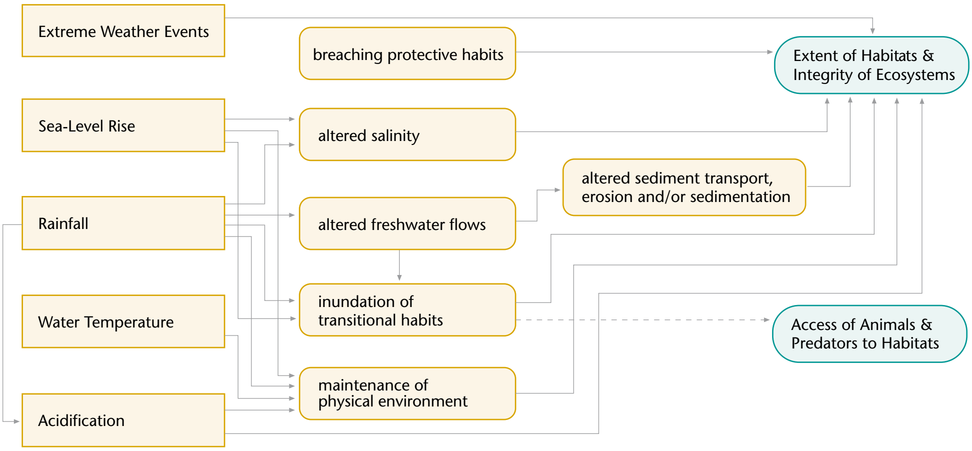
There are likely to be many changes to the extent of individual habitats and ecosystems, however, there is little certainty about the direction or extent of change, and the direction and extent of change is likely to vary spatially across a multitude of scales. Although our understanding is far from complete, there is considerable GBR specific detail for seagrass (Waycott et al. chapter 8), mangrove (Lovelock and Ellison chapter 9) and coral reef habitats (Fabricius et al. chapter 7). Unfortunately, this is not the case for many other habitats (eg estuaries, inshore benthic soft bottoms, coastal sandy intertidal, littoral wetlands) and habitat components (eg beaches, rocky intertidal, large woody debris (snags), salt marsh) comprising the CEM, although their location at the interface of land and sea makes them particularly vulnerable[43].

Impacts on habitats will be complex (Figure 19.2). The extent of vegetated habitats is likely to be impacted by interactions between changes in water temperature, sea level, rainfall, acidification and the frequency and intensity of severe weather events. The effects may also be indirect. For instance, tidal[39] and coastal wetlands that lie behind mangroves[45] and beaches[54] are particularly at risk if sea level rise leads to increased groundwater salinities[45] or if more frequent severe weather events[144] increases the breaching of protective habitats (eg mangroves or beach dunes).

The integrity of estuarine ecosystems depends largely on maintaining patterns of salinity distribution, including spatio-temporal profiles of hydroperiods, salinity gradients, and the position of the freshwater/estuarine interface[35]. These factors are functions of all aspects of flow; magnitude (volume), timing, frequency, duration of conditions, and rate of change of condition[24], and the interaction of these parameters with sea level rise[35] and tidal patterns.

Changes in timing and magnitude of flows alter sediment transport[10,11]. Altered river flows can lead to erosion or extensive sedimentation of estuaries[103,104], changing the nature and distribution of habitats. Modified flows can also reduce access to complex habitats in freshwater[21] and upper estuary

***Figure 19.2*** *Major likely impacts of climate change on coastal and estuarine habitats in the GBR region*



reaches[74], and reduce the erosion production of large woody debris, important as habitats for invertebrates and fish[131,136]. Consequently, populations of organisms relying on such habitats may decline and be replaced by ecological generalists[7]. On the other hand, sedimentation can lead to accretion that may allow many salt marshes to keep up with sea level rise[119]. Although this is only likely to occur where conditions are optimal for growth of salt marsh plants[5] and is dependent on the specifics of subsurface processes[25] and interactions with biotic factors[99].

Changes in sea level will directly affect the extent and periodicity of inundation of intertidal and estuarine wetland habitats of all types[134]. This will alter the nature of flora and fauna in areas that are presently intertidal, both because of physical tolerances to altered inundation levels[5], and because of changes in the prey, predators and competitors that can access intertidal habitats[16]. Other transitional habitats, such as those at the freshwater/estuary interface will be similarly affected, although in this case changes in rainfall patterns, as well as sea level changes, are likely to be important drivers[134].

From a general perspective, the effects of climate change on habitats may not be immediately obvious. Habitats are likely to be identifiable over time, although their locations and extents may have changed considerably. However, there is evidence from other climatic zones that although habitats and plant communities affected by sea level rise may appear similar, their underlying ecological functioning may be quite different to that before sea level rise[22].

### 19.3.3 Species and species-level ecological functions

There is considerable understanding of the likely effects of change on the distribution, growth and abundance of particular species and species groups (chapter 5 to 16). However, this information is lacking for the majority of species, and specific information on many species-level ecological functions is often not available. Additionally, most available information relates largely to estuaries, so prediction of likely impacts for other parts of the CEM can only be by extrapolation. Prediction is further complicated because, with such a diversity of species, habitats and physical conditions, any impact of climate change is likely to have different outcomes depending on the specific situation.

#### Flora

Freshwater flow and salinity are likely to have a variety of effects on plants (Figure 19.3). Variations in freshwater discharge have the potential to control the distribution and abundance of marine plants from phytoplankton[26] to macrophytes[6]. Change in salinity conditions can affect the growth and distribution of salt marsh plants[2] and even lead to the extinction of species[6], because different species have their own particular salinity requirements[5]. In fact, regular freshwater flooding is often needed to maintain salt marsh growth, reproduction and health[20]. At high topographic levels of the intertidal zone elevated salinities can lead to the accumulation of salt, restricting the distribution of macrophytes[6] including mangroves[41]. Even lower intertidal and subtidal plants, like seagrasses, have growth salinity optima[3], meaning salinity is important in determining their distributions[6]. Exacerbating the effects of flow on salinity, many salt marsh plants rely on freshwater seepage to maintain favourable salinity conditions[5]. Additionally, reduced flooding can limit the dispersal of mangrove propagules[115]. Where a lack of river flow prevents the opening of river mouths[156] tidal flooding, essential for some marsh plants[4], is reduced and exposure time of plants to desiccation increased[3].

Freshwater wetlands are already in a severely reduced state along the GBR coast with an estimated 80 percent reduction in area south of Cooktown since 1850[47]. Salinisation due to sea level rise will stress the remainder, although the extent of mangroves may increase if they can migrate landward. However, in general mangroves are in relatively good condition and under far less pressure than freshwater and estuarine wetlands. Sea level rise is thus likely to place extra stress on the most vulnerable component of the coastal wetland mosaic.

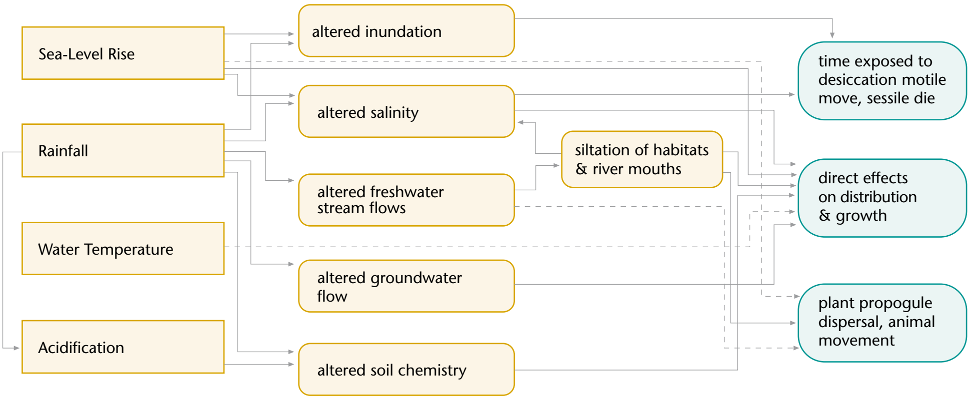
### Fauna

Effects of flow, and flow regulated salinity on fauna are more diverse and complex (Figure 19.3). Motile animals can move to accommodate changes in salinity, however, sedentary or sessile organisms may experience rapid changes in salinity levels or altered salinity conditions leading to metabolic stress, increased oxygen consumption and altered density of red blood cells[34,90,101,55,102]. In many cases organisms can make metabolic adjustments, but these come at the cost of degraded condition, reduced growth, greater vulnerability to other stressors[89,159] or impaired reproduction and recruitment[86].

Fish and pelagic and benthic invertebrates form distinct species assemblages along the longitudinal salinity gradients of estuaries[14,164,18], reflecting different salinity tolerances. These salinity tolerances may also be temperature dependent[23], presenting the possibility of interaction between the effects of altered rainfall and temperature change.

Changes in flow and salinity profiles can lead to substantial alterations in species distribution and abundance[77,130], or changes in patterns of habitat use[127]. However, the exact effects vary in space and time. In some situations high freshwater inflow to estuaries can enhance macrofaunal productivity[87] or fish abundance[68]. While in others, freshwater flows can lead to depressed abundances[161], produce population changes and even lead to the disappearance of some estuarine species[145,130]. These differences relate to such factors as the extent of connectivity to marine environments[145,134], the location of communities along the estuarine salinity gradient[130] and the type of estuary[18].

***Figure 19.3*** *Major likely impacts of climate change on plants and animals of coastal and estuarine habitats in the GBR region*



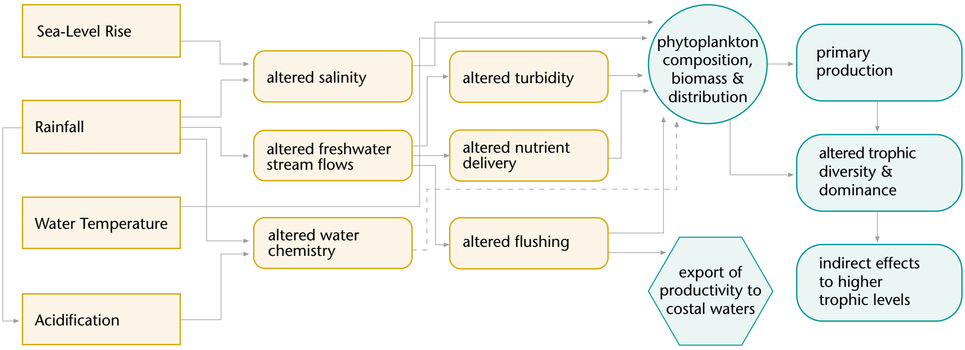
Additionally, responses tend to be species-specific with freshwater necessary to induce recruitment of low salinity species, while other species require more marine conditions[66]. Where hypersaline conditions omit species with low salinity tolerance, diversity and abundance may decline sharply[160]. In contrast, where constant high salinities result in estuaries becoming 'arms of the sea'[78] diversity may increase due to colonisation by stenohaline marine species[135]. This is likely to be at the expense of estuarine dependent species less tolerant of higher salinities[160]. Additionally, while changes to overall salinity levels may benefit some organisms, any advantage may be counteracted by other changes, such as increases in salinity variability[40].

### 19.3.4 Trophic function

Trophic function is likely to be affected by climate change both directly and secondarily through impacts on habitats, species distribution, abundance and connectivity (Figure 19.4). The direction and extent of change will depend on interactions at a range of scales. This uncertainty in outcomes is complicated because our understanding of trophic function of the CEM, and indeed of its individual components, is generally deficient. This lack of empirical understanding leads to a poor understanding of theoretical implications of change.

Effects of altered flow on estuarine food webs operate principally through stimulation of primary production, with effects then propagating upwards through food webs[67]. Changes in rainfall and freshwater flow have considerable implications for nutrient cycling and primary productivity in estuaries[84], with the biomass, productivity and community composition of estuarine phytoplankton extensively impacted by freshwater flows[30,84]. Variations in flow influence the supply of nutrients to estuaries[28], controlling inputs of phosphate, ammonium, nitrate and dissolved silicate[146]. For example, low flows during dry seasons or due to El Niño-Southern Oscillation (ENSO) driven disruptions of seasonal rainfall patterns both alter salinity patterns and reduce inputs of phosphorus to Everglade (USA) estuaries leading to alterations in nutrient processing[29]. The pattern of nutrient supply influences phytoplankton species composition because any reduction in dissolved silicate supply is likely to advantage flagellates (nonsiliceous and potentially harmful) while disadvantaging diatoms

***Figure 19.4*** *Major likely impacts of climate change on trophic function in coastal and estuarine habitats in the GBR region*



(siliceous and mostly benign)[56]. Additionally, silicate is potentially limiting to algal biomass in many ecosystems[70] with the potential to lead to low densities of diatoms and low algal productivity even in the face of adequate nitrogen and phosphorus. Any adverse impact on microalgae is likely to have far reaching impacts on estuarine productivity because microalgae are now recognised as among the most important primary producers in tropical estuaries[32]. The duration of flow events is also crucial because short-term freshwater flow events may not produce the lasting increases in inorganic dissolved nutrients[125] needed to benefit the productivity of phytoplankton communities[124].

As well as effecting nutrient supply, freshwater discharge affects residence time[26,46,29]. In high flow, residence time is short and most nutrients are washed through the estuary[46] but when residence time increases nutrients are retained in the estuary as biomass accumulates[46]. Additionally, changes in freshwater flows can modify the location and nature of salinity gradients[106] and alter the extent of intrusion of marine water into estuaries[26], altering the distribution of phytoplankton species and changing the succession between marine, estuarine and freshwater taxa. Alterations to the spatial distribution of phytoplankton can also impact productivity by modifying the spatial matching of the highly productive suspended particulate organic matter maximum to highly productive areas of the estuary (eg shallow bays[30]). Changes in turbidity or water colour due to altered freshwater flow can influence light attenuation[78,36], further impacting phytoplankton biomass and primary productivity. The combined effects of flows on nutrient supply and recycling, and the retention of phytoplankton mean that the pattern of freshwater flows both influences estuarine water column productivity and controls the delivery of nutrients to coastal waters[141].

Since effects of flow on estuarine food webs operate principally through stimulation of primary production[67] changes in freshwater flows that alter patterns of primary production can lead to substantial changes in trophic organisation[78,160]. For example, prolonged drought can lead to reduced abundance in particular trophic groups[134] and reduced trophic diversity (ie food webs are simplified), due to differential mortality and changing predation effects[134] and/or changes in nutrient cycling[77].

Even outside the estuary freshwater flows can have important effects. Floods export pulses of organic matter to near-coastal waters, leading to high abundances of detritus feeding invertebrates, such as polychaetes, and ultimately to increased abundances of predatory fish and enhanced fisheries productivity[120]. Consequently, the timing of flood pulses is likely to be important in supporting crucial life history stages in these habitats[120].

From an overall perspective, specific effects on food webs are diverse, complex and often difficult to predict. Trophic responses vary among groups. Since different trophic groups are often composed principally of particular taxonomic groups (eg herbivores and omnivores are often invertebrates while carnivores are often fish) they often respond to different factors (eg for invertebrates; physicio-chemical variables, for fish; biological factors)[77] However, although fish may not respond directly to flows, they are often impacted indirectly via food web interactions[77]. For example, in the Apalachicola Bay system, Florida, prolonged drought led to reduced fish richness, specific-abundances and trophic diversity principally through flow-on effects from alterations to nutrient cycling[77]. Additionally, effects can be contradictory. Increased light penetration due to reduced turbidity, resulting from reduced flow, can increase productivity and affect herbivore/omnivore abundance in coastal bays[78]. At the same time, low flows lead to lower nutrient loadings in estuaries resulting in severely reduced productivity[78]. In essence, under reduced flows, highly productive river-estuarine systems that previously had distinct

salinity gradients can become merely extensions of the sea[78,17,160]. Although the presence of marine species often leads to high species richness, productivity is often substantially impaired[78], abundances reduced[161], and ultimately fisheries production degraded[106].

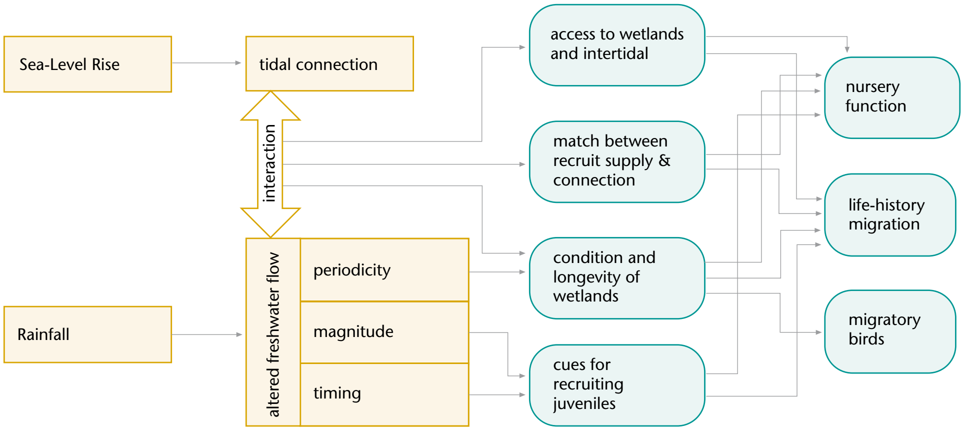
### 19.3.5 Connectivity

While the impacts of climate change on many aspects of the CEM are uncertain, potential effects on connectivity are much easier to evaluate. Depending on the scale and nature of the particular connection, sea level change, altered rainfall patterns, extreme weather events and secondary consequences arising from effects on habitats and species are likely to be influential (Figure 19.5).

Animals using wetlands need tidal and/or freshwater connections at specific times (eg when larvae are ready to recruit)[134]. Consequently, changes to base tidal levels or the magnitude or regularity of freshwater flows will be a major factor in determining the future success of wetland connectivity[134]. This effect is complex. For instance, the extent to which tidal connections penetrate salt marshes to replenish wetland pools depends on the pre-existing condition of the salt marsh surface. Tidal connections will occur more often and more extensively if the salt marsh surface is already wet from rainfall[134]. Any reduction in connectivity due to less regular rainfall will diminish the value of wetland nurseries to marine species, both because connectivity occurs less often, and because a reduced frequency of connection leads to pools drying out more often[134].

At a different temporal and spatial scale, change in sea level will alter the accessibility of intertidal regions to marine fauna. Rising sea levels will extend the time animals can spend in current intertidal habitats and the distance they can penetrate into them[152,153]. Although this will be offset because the intertidal zone will move as sea levels change, in many cases the effect is likely to be asymmetric.

***Figure 19.5*** *Major likely impacts of climate change on connectivity, migration and nursery ground function in coastal and estuarine habitats in the GBR region*



For example, rapidly rising sea level may allow mangrove forests to extend landwards (Lovelock and Ellison chapter 9), but while rising sea levels will eventually drown mangroves at the most seaward edges of mangrove forests[15], many plants will persist in the short term by extending pneumatophores vertically to continue to access oxygen when the roots are submerged[149]. Mangroves provide structurally complex habitat thought to be used as a refuge for fish[73]. Any landward progression of mangrove forests will be likely to enhance this refuge effect in the short term, with recently dead mangroves on the seaward edges of forests continuing to provide refuge habitat for some time.

In addition, there is likely to be a range of indirect effects on connectivity, as changes in the extent and proximity of habitats alter the nature and extent of connecting corridors[134]. For instance, major losses of intertidal seagrasses may adversely affect connectivity in areas where seagrass beds provide connecting habitats between coastal reefs and mangroves[91].

### 19.3.6 Migration

As is the case around the world[81,142], the volume, timing and duration of freshwater flows are crucial factors determining the ability of tropical estuarine fish to undertake migrations that are critical parts of their life histories (Figure 19.5). In the GBR region, this is the case for recreationally and commercially important species like barramundi, *Lates calcarifer*, and mangrove jacks, *Lutjanus argentimaculatus*,[117,118,50,134] as well as many other species of ecological importance[134]. Changes to climate patterns are likely to modify the biological usefulness of connectivity. A second factor that controls migration between estuaries and many wetland areas is the extent of tidal inundation of connecting channels[117,118,134], a factor that can be extensively modified by even small alterations in tidal level[117,118,134]. To complicate the problem, in many cases the extent to which tidal peaks connect estuaries and wetlands is greatly modified by sediment moisture levels of connecting channels[134], with rainfall prior to peak tides greatly enhancing connections. Consequently, alterations in rainfall patterns interact strongly with altered sea level to greatly affect the ability of fish to migrate between estuaries and estuarine wetlands[134]. Although, in some situations, it may appear superficially that increasing tidal levels will offset any effects of reduced or more periodic rainfall, this is unlikely to occur in most cases. The majority of Queensland coastal streams are already blocked by dams, weirs and other impoundments that impede fish migration[63,134], and the major human response to increased sea level is likely to be the construction of even more barriers.

Beyond the effects on fish, GBR estuarine wetlands are nursery grounds for important crustacean species, such as commercial penaeid prawns[138], which have the same requirements for effective connectivity. In addition, freshwater flows have species-specific impacts on abundance of migrating water birds on estuarine mudflats, with both high and low flows potentially problematic depending on the particular estuary and species involved[107]. Furthermore, altered rainfall patterns modify salinity profiles and the persistence of wetland pools, affecting both their viability as fish habitats[134] and as feeding grounds for migrating water birds[69,134].

### 19.3.7 Nursery grounds

Estuarine wetland and connected freshwater areas are crucial juvenile nurseries for many species[13,94,147,95]. In the GBR region this includes commercially and recreationally important species like barramundi[117,118,63,134] and mangrove jack[131]. Climate change, particularly through altered freshwater

flows, is likely to profoundly influence nursery ground function because it directly affects assemblage composition, abundance, growth of juveniles[117,13,71,134], the viability (persistence before drying out, salinity levels and temperature) of the habitats as effective nurseries[134] and the ability of juveniles to enter and leave nursery grounds (Figure 19.5).

Implications of climate change for nursery grounds go far beyond this however. Too little flow may alter the strength and position of the estuarine turbidity maximum, an area where larval fish aggregate[94,148], particularly those requiring reduced salinities. Reduced flow may also fail to provide sufficient cues to marine larvae using salinity or other signals transmitted through flows to find and enter estuaries[147,160]. In contrast, too much flow can flush estuary-resident species from the upper reaches of the estuary[148] and render conditions unsuitable for species requiring higher salinities. The timing and extent of freshwater inflow is also important in the provision of appropriate shallow water nursery habitat[72], ensuring the supply of nutrients to estuarine and wetland nurseries[110], and in supporting the complex productivity patterns that support species-specific feeding patterns crucial to nursery ground utilisation[77]. In addition, the recruitment success of marine species is likely to be strongly influenced by the timing of freshwater flow events[132], with the potential for recruitment failure if the occurrence of flows fails to match the availability of recruiting larvae[155].

### 19.3.8 Higher-level ecological functions

Again, effects of climate change on higher-level ecological functions are likely to result from complex interactions of effects at lower levels[77,67], making detailed prediction impossible at this time. However, in a general sense, major climate change is likely to alter the nature of communities and community interactions in pervasive ways. For example, the small amount of research available from quite diverse taxonomic groups[76,137,130] indicates considerable differences in composition and function of Queensland's wet and dry tropical estuarine fauna. Consequently, a reduction in the amount or regularity of rainfall in the wet tropics could move those ecosystems towards dry tropics composition and functioning, with obvious flow-on effects for other components of the CEM. Similarly, the dry tropics would probably move towards wet tropics functioning with increases in the amount or regularity of rainfall. Therefore, while a functioning habitat would be maintained, it could be quite different to that operating pre-climate change. Such changes would probably extend across most higher-level functions (Table 19.1), although at present there is no knowledge base that would allow the implications of changes to these functions to be quantified. Additionally, while switches between dry and wet tropical climates would be likely to produce fairly predictable outcomes, there is no way of predicting the outcomes for dry tropics of lower, less regular rainfall, or for wet tropics of higher, more regular rainfall.

At a different scale, dominant patterns of coastal production are likely to change substantially. These depend on interactions between biological components and a suite of environmental factors such as rainfall, river flow, tidal action and turbidity[51]. Consequently, through changes to these factors and effects on diversity and species composition, major changes in weather patterns have great potential to alter patterns of habitat productivity. While the outcomes of such changes would still be functioning habitats, the natures of the resulting habitats are likely to be quite different to those prior to climate change.

### 19.3.9 Diversity

The strong relationships between species and their habitats[19] means changes to the presence, extent, boundaries or connectivity of habitats and ecosystems are likely to directly impact the range of species able to use them. Additionally, changes in the extent of habitats will be likely to directly influence species richness because the number of species is highly correlated with habitat area (the well-known species-area relationship[83]). Changes to environmental conditions (eg temperature, salinity, rainfall patterns and environmental stability) will also lead to changes in diversity because these factors are major determinants of the distribution of species[44]. Resulting changes in the presence and abundance of predators, prey and competitors will further modify species richness[38]. Additionally, any change in the frequency or intensity of extreme weather events (cyclones or major floods) is also likely to directly impact species richness because the nature of the species present (eg opportunistic versus persistent[151]) and the number of species[82] is correlated with disturbance frequency.

Changes in habitat availability, extent, proportion and/or connectivity are also likely to affect the diversity of ecological function. Diversity of function is probably even more important than species diversity, because diversity of function feeds back to determine the identity and number of species present, as well as influencing ecosystem stability[62].

### 19.3.10 Estuary health and resilience

Effects of climate change, such as alterations to freshwater inflow to estuaries, are likely to influence overall estuarine health, and the resilience of estuarine habitats to human impacts. Water quality (flow, chlorination, temperature, dissolved oxygen, pH and suspended solids) is affected by drought[12], and freshwater flows can be important in diluting pollutants and maintaining oxygen levels[100]. Reduced freshwater inputs can enhance eutrophication in polluted estuaries due to decreased flushing potential of the estuary[126], and the interaction of flow-induced changes in the nutrient environment, elevated nutrient levels due to anthropogenic pollution, and alterations in phytoplankton composition. One potential consequence of this is increased likelihood of cyanobacteria blooms[28,113,37].

### 19.3.11 Interactions with anthropogenic factors

Complicating the potential for impact on the diversity of physical, biological and functional aspects of the CEM is the problem of interactions between the effects of climate change and anthropogenic factors. These take two forms. Firstly, the heavy pressure from human activities on many habitats (eg estuaries[65]), habitat components (eg mangroves[96]) and at-risk species (eg dugongs[59]). Secondly, the inevitable changes produced by human responses to the effects of climate change such as the construction of dams and walls to prevent tidal incursion into wetlands[63,134] and croplands. Existing bunds are a major factor in the disruption of estuarine connectivity in areas of the lower Fitzroy catchment[63,134]. These interactions between climate change and human responses have the potential to impact the CEM as profoundly as climate change itself[57]. As well as reducing connectivity between estuaries and coastal wetlands, the construction of barriers to prevent inundation from sea level rise is likely to greatly reduce connectivity, and prevent the landward advance of mangroves, salt marshes and seagrass meadows that would compensate for seaward losses[42]. Similarly, dams built to increase the storage of water under drying conditions, or control flooding under conditions of

increasing rainfall, would hamper connectivity and impede the delivery of nutrients to estuaries and other coastal habitats[53,140]. Many estuaries on the southern and central GBR coast have already been significantly modified by agricultural and urban development. While fundamental understanding of estuarine ecosystems is quite limited[134], it is clear that their ability to respond to the impacts of climate change will be constrained by these human modifications, for example channel structures and hard boundaries with agricultural and urban land[92].

The Fitzroy estuary in the southern GBR catchment provides examples of these types of modifications and the pressures they place on the resilience of estuaries in relation to climate change. The Fitzroy estuary is a large tide-dominated estuary characterised by mangrove-lined tidal creeks backed by extensive salt marsh and salt flats that merge with the freshwater reaches of the lower floodplain. In the north of the estuary, tidal creeks have been dammed to provide freshwater pasture (ponded pasture) for cattle grazing (Figure 19.6). In the south, extensive areas of salt marsh, salt flat and adjacent floodplain have been converted to evaporation ponds for the production of salt (Figure 19.6), and the landward limit of tidal influence has been reduced by a tidal barrage on the Fitzroy River at Rockhampton. These structures have obviously reduced the area of wetland and form hard boundaries with estuarine habitats (Figure 19.7). They will constrain the potential responses of the estuary to climate change because:

i) they limit the ability of habitats to shift in response to the predicted rapid rise in sea level, for example the back stepping of intertidal habitats such as salt marsh and mangroves[166],

ii) they effectively sequester large areas of floodplain that could be colonized by intertidal species in response to sea level rise,

iii) they will result in additional changes in the areal proportions of estuarine habitats as the estuary adjusts to sea level rise, and

iv) they may further influence the hydrodynamics of the estuary under a rising sea level.

Even without human responses to climate change, interactions with human development are likely to complicate and magnify impacts on coastal habitats. For example, land clearing alters drainage patterns and interacts strongly with changes in rainfall to influence downstream flows and sediment loads[26,9,27,116]. Similarly, because of their proximity to human population centres and ports, coastal ecosystems and habitats are under heavy developmental pressure. Areas of habitats such as mangroves and salt marshes[123], and seagrass beds[42] continue to diminish as intertidal and supra-tidal wetlands are reclaimed for ports, marinas, housing developments and aquaculture ventures to name a few. Altered hydrologic regimes due to climate change could further exacerbate encroachment of agricultural land-use into wetlands[57]. Freshwater wetlands are likely to be squeezed between fixed (and protected by bunds from salt water intrusion) coastal cropping lands (sugarcane in particular) and encroaching marine wetland systems (mangroves and salt marsh). This will impinge on species such as barramundi given the importance of the complete range of coastal wetlands for such species.

These human pressures are likely to work in the same direction as the effects of climate change, both amplifying any adverse effects and reducing the ability of habitats to respond positively.

***Figure 19.6*** *Landsat image (2003) of the Fitzroy estuary, southern GBR coast, showing the location of dams across tidal creeks to provide ponded pasture (P) and inter and supra tidal areas converted to evaporation ponds (E)*

***Figure 19.7*** *Aerial photograph (2003) showing one of the ponded pasture dams (P) indicated in Figure 19.6. The dam forms a hard boundary between mangroves (green) and pasture (brown)*

## 19.4 Adaptive capacity

In a general sense, coastal habitats have a demonstrated capacity to respond to climatic change as there have been many changes in the past and the habitats have persisted[58]. Over geological times coastal systems have adapted to sea level changes, as evidenced in the pollen record. However, changes due to human activities in these ecosystems have led to ecological changes that appear to be beyond the adaptive capacity of the ecosystems[1,154]. Additionally, substantial adaptation to large-scale change is likely to mean substantial habitat change, in most cases to unknown or at least unpredictable states. While there is probably little that can be done to prevent ecosystem-scale change, it will be important to do everything possible to prevent interactions with anthropogenic factors that lead to degraded habitats and impaired ecosystem function.

At a more specific level, a lack of a sufficiently detailed knowledge base means it is difficult to predict the adaptive capacity of individual components of the CEM in the face of forces of climate change that can impact at a variety of conceptual scales. An example, will illustrate this point. The barramundi, *Lates calcarifer*, is an iconic component of GBR coastal habitats. Barramundi have formidable abilities to thrive across a very wide range of environmental conditions, from freshwater to hypersaline conditions[150]. At face value barramundi should be well equipped to deal with climate change, they should be able to utilise alternative habitats if usual habitats become unavailable in a particular area. It is even possible that the ability to utilise a diversity of habitats will greatly reduce the likely impacts of reduced connectivity[134]. However, we also know that barramundi exist as a number of distinct stocks along Queensland's east coast, with each tending to be confined to a particular climatic region[129]. The implications of this stock structure are not yet understood. For instance, different stocks appear to use nursery grounds differently. Since we do not know the extent to which populations can adapt to different nursery ground availability, we can not be sure if the ability to use a variety of habitats, which is obvious at the species level, translates to a similar ability at the population level; the level where adaptation to climate change will be necessary. What is alarming about this is that barramundi are probably by far the best understood coastal marine species in the GBR region.

## 19.5 Summary and recommendations

### 19.5.1 Major vulnerabilities to climate change

There is little doubt that coastal and estuarine habitats and ecosystems in the GBR region will be severely impacted by climate change. They are particularly vulnerable to four aspects of climate change: i) alterations in the magnitude, timing and frequency of rainfall, ii) sea level rise, iii) altered frequency and severity of extreme weather events, and iv) major changes in water temperature. Changes to rainfall patterns are likely to have the most diverse and far reaching effects because it is the mixing of fresh and marine waters that give estuaries their unique characters, and because freshwater delivers nutrients from the land that supports estuarine and coastal productivity.

Altered rainfall is likely to profoundly affect individual species and their distributions, the habitats they rely on, the trophic webs that support them and ecological processes like migration and nursery ground function. Changes in rainfall will manifest its effects through impacts on salinity, nutrient delivery and export, flushing, sediment transport, inundation, habitat availability and the cuing of recruits to enter estuarine nurseries (Figures 19.2 to 19.5). Rainfall will also interact strongly with sea level rise to determine crucial connectivity, wetland health and persistence, and nursery ground availability and value, as well as impacting inundation levels and salinity to affect the very nature of estuaries (eg shifts between dry and wet tropics estuarine conditions). Changes to the timing and frequency of extreme weather events is likely to disrupt the normal cycle of variability and resetting (essential in maintaining estuarine productivity, trophic structure and habitat diversity), alter patterns of diversity through time, influence the rate of habitat destruction, and change the extent of opening of estuary mouths.

### 19.5.2 Potential management responses

While impacts of climate change on coastal and estuarine habitats seem inevitable, effects can be ameliorated by careful management of human responses to climate change. In this regard much can be done. It is of primary importance that dams and weirs used to impound freshwater, and bunds and other barriers built to prevent the ingress of marine waters, are constructed sparingly. Where they must be constructed every effort should be made to maximise normal biological connectivity (not just the movement of organisms but all aspects of biological connectivity), and ensure that flows into estuaries are sufficient and correctly timed, to meet the ecological needs of estuaries and coastal waters (eg nutrient and sediment supply, maintain recruitment to nurseries). In addition, current barriers that are not essential should be identified, and where possible removed. This is particularly important where hard barriers limit the landward progress of wetlands and intertidal habitats (eg mangroves and seagrass) able to respond to sea level rise by moving landwards to occupy newly available niches. Even given the most stringent management, human response to climate change will inevitably lead to some loss of connectivity and reduction of current wetland area. This makes careful management of future development of wetlands for agricultural, commercial and urban development crucial, and means that current developments need to be reviewed to determine ways in which their present and future impacts can be minimised. Finally, it will be crucial to carefully control human activities (eg land clearing and coastal development) that impact the delivery of sediment, nutrients and pollutants to estuaries and coastal ecosystems.

### 19.5.3 Critical knowledge gaps and future research

Compared to knowledge of coral reefs or freshwater streams, understanding of coastal ecosystems of tropical Australia is deficient. Some individual habitat components (eg mangrove and seagrass) have received some attention but are still poorly understood. For many other habitat components (eg salt marshes, fresh and salt water coastal wetlands, soft bottom communities, inshore pelagic communities) there is little region-specific understanding. Ecosystem-level understanding is even more limited, even for estuaries that occupy a vital, central position between land and sea, while understanding of the complex interlinking of habitats and ecosystem components is almost non-existent. Consequently, there is a broad spectrum of knowledge gaps. Some of the most basic and most likely knowledge gaps that will impair responses to the threat of climate change are discussed below.

#### Connectivity

Even though coastal habitats are extensively interlinked, and crucial processes like nursery ground provision are underpinned by connectivity, there is a poor and simplistic understanding of connectivity. In fact we have not even documented the full extent of connectivity or the processes they facilitate and depend on.

### Effects of flow on tropical coastal systems

Among the most likely consequences of climate change are alterations in rainfall intensity, duration and variability, all likely to modify the pattern of freshwater inflow and delivery of nutrients and other materials to coastal habitats, and greatly impact connectivity. We have little understanding of the ecological importance of freshwater to tropical marine ecosystems, let alone knowledge of the likely effects of change.

### Diversity and function

At a very basic level, understanding of the diversity of life and the diversity of ecological function of tropical coastal ecosystems is data limited, even for the better studied components. Many groups are poorly characterised and their distributions little understood at any scale.

### Habitats

Similarly, there are many gaps in understanding of habitats, inter-habitat relationships and organism-habitat relationships, so little understanding of how changes to these will impact organisms and ecosystem function.

### Life-cycles

The life cycles of most species are poorly understood. For instance, a lack of knowledge of the juvenile habitats or environmental requirements of a majority of species translates to a poor understanding of potential impacts of climate change on this crucial life-history stage.

### Wet versus dry tropics

At a more specific focus, there is little understanding of the differences in composition and function of wet and dry tropical habitats, although climate change is very likely to cause shifts between these states, and even see individual systems fluctuate between these extremes.

### Interaction with anthropogenic responses

From a management perspective, there is a need for detailed investigation of ways to minimise the impacts of anthropogenic responses to climate change on coastal ecosystems. Overall, although there are many and diverse specific gaps in understanding, the major deficiencies are in 'big picture' understanding. While more encompassing studies, focussing at this conceptual level, are obvious priorities, well-directed studies of specific aspects will also be required to underpin them.

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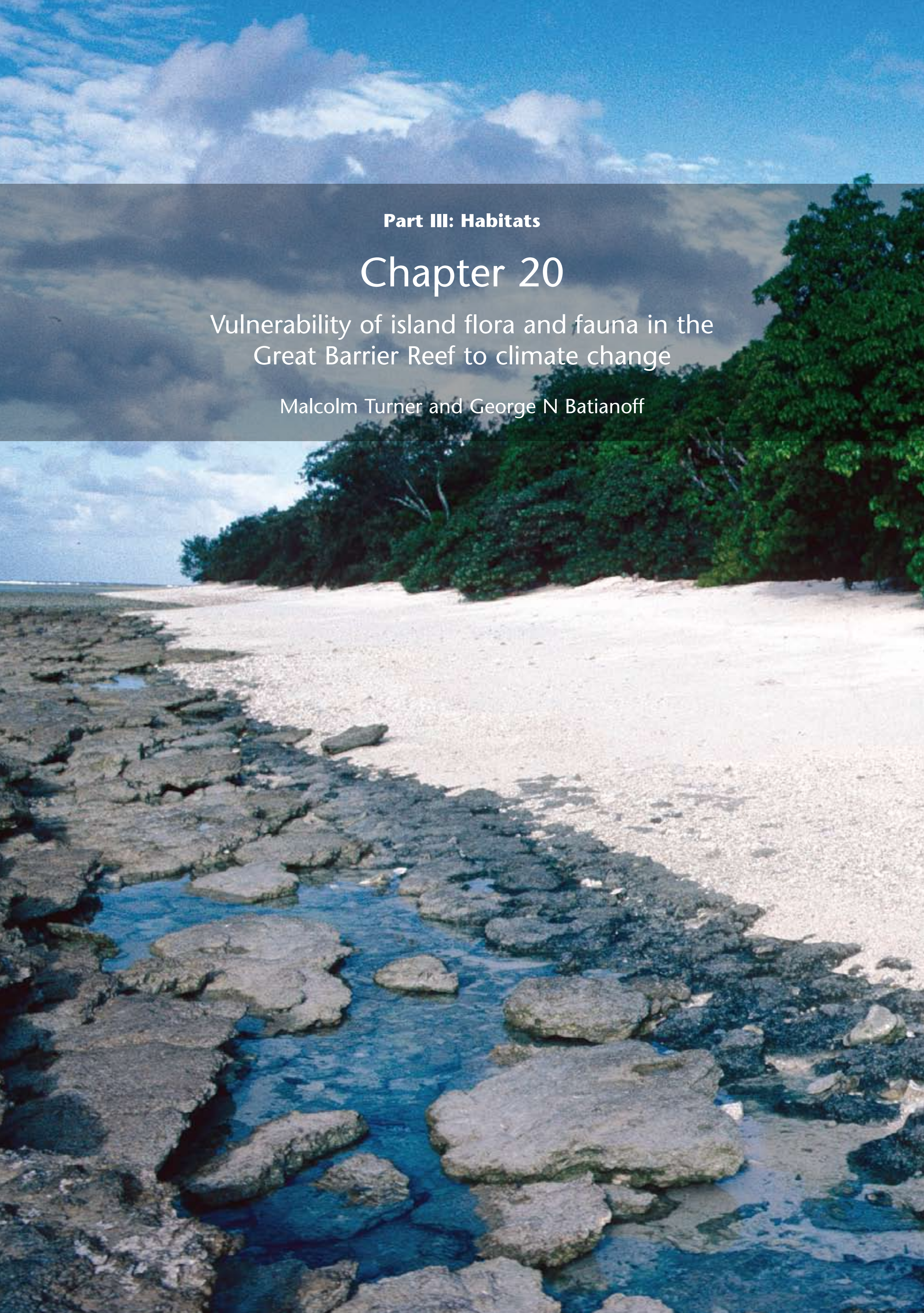
**Part III: Habitats**

# Chapter 20

## Vulnerability of island flora and fauna in the Great Barrier Reef to climate change

Malcolm Turner and George N Batianoff



## 20.1 Introduction

The emphasis of this chapter is on terrestrial and freshwater flora and fauna, and key nesting habitats on the islands of the Great Barrier Reef (GBR). This chapter should be read in conjunction with other chapters of this volume detailing the specific effects of climate change on different components of island habitats: mangrove and tidal wetlands are discussed in chapter 9, seabirds in chapter 14, marine turtles in chapter 15 and geomorphology in chapter 21.

Below is a brief description of flora and fauna of islands in the GBR. For more information refer to the State of the GBR[24]. Several references are made to threatened species in this chapter. Unless otherwise stated, the status refers to Queensland threatened species status[a].

### 20.1.1 Islands of the Great Barrier Reef

The GBR includes about 900 islands, of which approximately 600 are continental or high islands (Smithers et al. chapter 21). The majority of these high islands are composed of granite or their volcanic equivalents (rhyolite or acid volcanic), with some mixing with other rock types on some islands[51]. Some of the inshore islands in the southern GBR are predominately sand islands. The largest continental islands are Curtis, Hinchinbrook and Whitsunday Islands (Figure 20.1). Approximately 300 low islands or coral cays are found in the GBR. They are formed by the accumulation of sediments on reef flats. Shingle cays form on the windward side of reef flats and sand cays on the leeward side (Smithers et al. chapter 21). There are 44 low wooded islands in the northern half of the GBR, which has both shingle and sand cays, cementation of beach rock and mangroves on the reef flats[57].

The types, formation, and distribution of islands within the GBR are discussed in Smithers et al. (chapter 21). Smithers et al also discuss climate change vulnerabilities with some changes leading to an increase in island size and other impacts leading to a decline in the number and area of islands.

Most GBR islands are north of the Tropic of Capricorn and are considered ‘tropical’. They receive approximately 80 percent of their rain in the summer wet season with the rest in the winter dry season (Lough chapter 2). Most of the Capricorn Bunker Group, the Swains Cays and the southern inshore sand islands are south of the Tropics and considered ‘sub-tropical’. These islands have some influence from winter rains. The boundary between tropical and sub-tropical regions is a gradation affected by temperature, aspect and elevation.

Islands are an important component of the GBR ecosystem. Several species of terrestrial flora are endemic to the islands. Some habitats, such as pisonia closed-forests, are largely confined to the islands. The intertidal habitats of islands including mangroves, beaches, rocky shores (including beach-rock shores on coral cays), and coral reef flats provide living space and nesting sites for a range of marine and terrestrial plant and animal species, including turtles, seabirds and shorebirds. Freshwater wetland habitats are scarce on the low islands, however several larger continental islands have seasonal streams and swamps that frequently dry out in the dry season. For example, Hinchinbrook and Magnetic Islands have melaleuca wetland habitats and Hinchinbrook Island features a continuous supply of freshwater creeks[77]. Many islands have salt marsh and mangrove wetlands.

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[a] Environmental Protection Agency (2007) http://www.epa.qld.gov.au/nature_conservation/wildlife/threatened_plants_and_animals

***Figure 20.1*** *Map of the GBR region indicating key islands and their locations*

## 20.1.2 Terrestrial flora

To understand the potential effects of climate change on the flora of GBR islands, awareness of the baseline flora is necessary. The following section describes the flora of GBR continental islands, low islands and coral cays before advising about the potential effects of climate change on the islands.

### *20.1.2.1 Flora of continental islands*

Approximately 2000 native species of vascular plants have been recorded on continental islands and low sandy mainland islands within the GBR, representing a quarter of Queensland's vascular flora[9]. About 70 (less than 5%) of these plant species are listed as rare and endangered in Queensland[111], and eight species are considered as endemic to the continental islands within the GBR (see Table 20.1).

Vegetation types on continental islands range from rainforest to dry open-woodlands and grasslands. Woody species comprise 70 percent of the island flora in the north of the GBR, gradually reducing to 50 percent of the island flora below the Tropic of Capricorn[9]. The majority of plants in the north of the GBR are rainforest species and this trend continues south to the Whitsunday region where an equal number of rainforest and open-forest species occur. Further south in the Capricornia region, 65 percent of the flora belongs to open-forest communities, including an increased number of grasses[9]. Differences in species composition reflect the location of each island, and differences in response to climate change are likely to reflect this.

Floristic analyses of the continental islands in the GBR indicate that an increased distance from the mainland results in decreased floral species richness. Batianoff and Dillewaard[9] found that species diversity increases linearly with island size up to 5000 hectares. For islands larger than 5000 hectares, other factors such as habitat diversity, remoteness, paleo-climate and fire activity also

***Table 20.1*** *Plant species endemic to Great Barrier Reef islands*

| Species | Location | Details |
|---|---|---|
| Albizia<br>(*Albizia* sp.) | South Percy Island | Beach scrub small tree<br>(GN Batianoff 11444) |
| Allocasuarina<br>(*Allocasuarina* sp.) | Shaw Island (Whitsunday Group) | Open forest tree<br>(GN Batianoff 3360) |
| *Berrya rotundifolia* | Calder (Cumberland Group) and Middle Percy Islands | Vine scrub tree – rare status |
| *Buchanania mangoides* | Central GBR islands | Rainforest tree – rare status |
| *Gossia* sp. | Lizard Island | Open-scrub shrub species<br>(GN Batianoff AQ 454451) |
| *Kunzea graniticola* | Hinchinbrook Island | Scrubland shrub |
| *Psychotria lorentzii* | Lizard Island | Vine scrubland, scrambling shrub – rare status |
| *Tetramolopium* sp. | Mt Bowen on Hinchinbrook Island | Scrubby herb – rare status<br>(DG Fell+ DGF1224) |

determine species richness[9]. The vegetation of Hinchinbrook Island is diverse due to the island's size, height and proximity to the mainland. Of particular interest are the montane heaths, dominated by banksias and casuarinas, which are confined to the island's mountains. The cooler peaks have a more continuous supply of moisture brought by south-easterly winds than the lower parts of the island. Eight species of orchids only grow in rainforest pockets above 700 metres in altitude (W Lavarack pers comm). Another unusual type of vegetation is found on the dune complexes on the northern part of Hinchinbrook Island[29].

The proximity of an island to the mainland also affects the arrival of new species. Some components of the vegetation of continental islands, such as the hoop pine (*Araucaria cunninghamii*) on Lizard Island, are remnant from when the islands were connected to the mainland during the last ice age. Other species that have successfully colonised islands arrived by sea-dispersed seeds or other propagules spread by wind, birds or fruit bats.

### 20.1.2.2 Flora of coral cays and low islands

The species richness of coral cays of the GBR is affected by their location and size. Within the GBR, coral cays and low islands are more numerous on the inner and outer shelves of the far northern section of the GBR, with larger coral cays occurring in the Capricorn Bunker Group in the southern GBR. The northern low islands are more complex, with greater species richness than southern cays[110,40,116]. Some 200 to 250 native vascular plants are recorded north of latitude 16° 57' S and only 80 to 90 are recorded on southern cays.

The ecological factors differentiating these two regions are that many northern low islands are closer to the mainland and experience more tropical conditions with higher rainfall and more cyclones. As a result, the northern cays have more complex low wooded habitat with mangroves, and contain many woody beach scrub and littoral rainforest species. In the southern region many islands have a higher winter rainfall, and, as the distance from the mainland is greater, fewer seeds are brought by terrestrial birds. The result is that there are fewer rainforest species, and about 50 percent of the native flora is herbaceous (Batianoff unpublished data).

Freshwater availability is limited on coral cays. Surface freshwater rarely occurs on sand or shingle islands, but freshwater frequently occurs in a subterranean freshwater lens that floats within the centre of the island with saltwater to the sides and below. In areas where rainfall is low, this freshwater lens is an important factor in coral cay ecology.

### 20.1.2.3 Physiological aspects of flora

Carbon dioxide gas in the atmosphere is utilised by plants during photosynthesis and its availability limits plant growth. According to Drake et al.[31] and Lovejoy and Hannah[76], terrestrial plants belong to three major groups based on their differences in photosynthetic processes and productivity. These plant groups are referred to as $C_3$ (includes about 95% of the world's flora), $C_4$ (about 4%) and Crassulacean Acid Metabolism (CAM) plants (about 1%). The terrestrial plants of the GBR include all three forms of photosynthesis. The ancestral $C_3$ plants are represented by the woody species of rainforests, open-forests and shrublands, and the non-woody sedges and rushes of wetlands. The $C_4$ plants are predominantly the tropical grassland and savannah species. In the GBR the succulent CAM

plants, which globally are considered species of desert and semi-arid ecosystems, are mostly found in the saline herblands at the inter-tidal margins.

The impact of climate change on island flora will largely be determined by the differences in photosynthetic potential of each plant group present in island environments.

### *20.1.2.4 Fire*

Fires started by lightning strikes are a natural part of the Australian environment and various species and ecosystems have developed adaptations to survive fire[108]. The vegetation reflects an area's fire regime, which is defined by fire intensity, fire frequency, and the season of burn[119]. Any change in fire frequency is likely to have major impacts on the composition, age-distribution and biomass of forests and rangelands[67,3]. In Australia fire management considers the concept of fire danger, which is a combination of the chances of a fire starting, its rate of spread, intensity and the difficulty of its suppression[119].

The burning of vegetation on GBR islands by humans has occurred for thousands of years, first by indigenous peoples and then by early European settlers. The Queensland Parks and Wildlife Service (QPWS) aims to manage fire frequency with regard to historic human burning patterns[98]. Grasslands on several continental islands in the GBR, such as the Whitsunday and Flinders Groups, are ecologically maintained using prescribed burning to prevent invasion of grasslands by shrubs. Heathland on Hinchinbrook Island is regularly burnt at an interval of several years to prevent invasion by ferns and rainforest.

## 20.1.3 Fauna

Much of the terrestrial fauna on islands is similar to populations on the adjacent mainland, but with fewer species. Some species, such as the yellow spotted goanna (*Varanus panoptes*) of Lizard Island, were stranded on islands as sea levels rose following the last glaciation several thousand years ago. Other fauna species are more widespread as they can colonise by air (eg bats) or on floating vegetation (eg rats).

Some significant terrestrial fauna of GBR islands are listed in Table 20.2.

### *20.1.3.1 Reptiles*

At least 40 species of terrestrial reptiles, including 31 lizards and nine snakes, are found on the islands of the GBR[50]. Most of these reptiles occupy similar habitats to those they occupy on the mainland. Species richness decreases with increasing latitude and increasing distance from the mainland[81]. A number of lizard species are endemic to GBR coral cays[50].

Thirty-eight islands have important marine turtle nesting sites, especially Raine Island, Milman Island and the cays of the Capricorn Bunker Group. Globally important populations of loggerhead (*Caretta caretta*), green (*Chelonia mydas*), hawksbill (*Eretmochelys imbricata*) and flatback (*Natator depressus*) turtles[74] nest at these sites. Turtles nesting in the littoral vegetation zone of coral cays and continental islands physically disturb island vegetation. Estuarine crocodiles (*Crocodylus porosus*) and, inhabit mangrove islands and low wooded islands, visit islands well offshore in the far north[82], and breed at Deluge Inlet and several creeks of Hinchinbrook Island[99]. For impacts of climate change on marine reptiles see Hamann et al. (chapter 15).

**Table 20.2** *Significant terrestrial fauna of Great Barrier Reef islands*

| Species | Location | Notes |
|---|---|---|
| Proserpine rock-wallaby (*Petrogale persephone*) | Gloucester Island, Hayman Island (Whitsunday Group) | Endangered. On mainland and two islands[87] |
| Bramble Cay melomys (*Melomys rubicola*) | Bramble Cay | Endangered. Endemic to the cay[73] |
| Northern quoll (*Dasyurus halluctatus*) | Magnetic Island | Rediscovered on Magnetic Island (G Ryan pers comm) |
| Coastal sheathtail-bat (*Taphozous australis*) | Magenetic Island | Vulnerable. |
| Koala (*Phascolarctus cinereus*) | Magnetic Island, St Bees Island (Cumberland Group) | Introduced, but stable populations |
| Striped–tailed delma (*Delma labialis*) | Magnetic Island | Vulnerable in Action Plan for Australian Reptiles[25] |
| Sadliers dwarf skink (*Menetia sadlieri*) | Magnetic Island | Endemic to the island[83] |
| Common death adder (*Acanthophis antarcticus*) | Gloucesfer Island | Rare. Death adders on adjacent mainland are northern species |
| Rusty goanna (*Varanus semiremex*) | Magnetic Island | Rare. |
| Dawson yellow chat (*Epthianura crocea macgregori*) | Curtis Island | Critically endangered in Action Plan for Australian Birds[44] |
| Capricorn white-eye (*Zosterops lateralis chlorocephala*) | Capricorn Bunker Group | Endemic to the island group |
| White-rumped swiftlet (*Collocalia spodiopygius*) | Dunk Island | Rare, nests in caves |
| Whitsunday azure butterfly (*Ogyris zosine zolivia*) | Whitsunday Group | Endemic to Whitsunday Group. Habitat dependent[113] |
| A skipper butterfly (*Hesperilla malindeva dagoomba*) | Magnetic Island, Scawfell Island (Cumberland Group) | Recently described, endemic to GBR islands |

### 20.1.3.2 Coastal birds

Birds of the GBR may be categorised as seabirds, shorebirds, waterbirds and terrestrial (or land) birds. Approximately 215 species of birds have been reported from the GBR but many are not resident[111].

#### Seabirds

Climate change impacts on seabird feeding and breeding success is discussed in Congdon et al. (chapter 14). This chapter considers the impact on the island nesting habitat of seabirds and other birds.

Fifty-five islands have been identified as the most important seabird breeding islands of the GBR[66]. Approximately 736,000 pairs of seabirds of about 24 species were reported breeding in the GBR in 1995[117]. Some significant seabird species are listed in Table 20.3. About 80 percent of seabirds breed on low islands such as coral cays and 20 percent breed on high continental islands, with most breeding in the far north or southern regions of the GBR[58]. Distribution depends on the suitability of the islands as nesting sites and the proximity of suitable food. Faeces, food scraps, dead chicks and expired adults are a major source of nutrients for plants on many islands and some species such as pisonia thrive on these nutrients.

Key seabird populations have declined in recent years at four localities on the GBR[112]. According to Batianoff and Cornelius[8], a comparison of Raine Island's breeding seabird populations from 1979–1993 to 1994–2003 showed a greater than 65 percent reduction in population size for five species of seabirds. These were the red-footed booby (*Sula sula*) (68%), lesser frigatebird (*Fregata ariel*) (68%), bridled tern (*Sterna anaethetus*) (69%), sooty tern (*Sterna fuscata*) (84%) and common noddy (*Anous stolidus*) (95%). Batianoff and Cornelius[8] and other authors have suggested the declines at all four localities are related to warmer water affecting food availability rather than impacts of human disturbance or other impacts on the nesting islands (see Congdon et al. chapter 14).

### Shorebirds

Shorebirds feed on the mudflats and beaches of GBR islands and the adjacent mainland. Some significant shorebirds are listed in Table 20.3. Several species are resident all year and breed on remote island and mainland beaches. Hundreds of thousands of migratory shorebirds from the northern hemisphere utilise the GBR as a wintering ground, or on passage to and from wintering grounds further south. Many of the shorebirds and seabirds of the GBR are listed under international treaties for the protection of migratory birds[111].

***Table 20.3*** *Significant seabirds and shorebirds of Great Barrier Reef islands*

| Species | Location | Notes |
|---|---|---|
| Little tern (*Sterna albifrons*) | Widespread in small colonies | Endangered in Qld. Nests on sand spits |
| Roseate tern (*Sterna dougallii*) | Swain cays, Capricorn Bunker Group | Internationally threatened. Both migratory and breeding populations |
| Herald petrel (*Pterodroma heraldica*) | Raine Island | Endangered in Qld. On edge of range. A few pairs only |
| Red-tailed tropicbird (*Phaethon rubricauda*) | Raine Island, Lady Elliott Island | Vulnerable. Several nesting pairs |
| Beach stone-curlew *(Esacus neglectus*) | Widespread but rare on inshore islands | Vulnerable. Nests on isolated beaches. Resident shorebird |
| Sooty oystercatcher (*Maematapus fuliginasus*) | Widespread but rare on rocky inshore islands | Rare. Resident shorebird. Nests on isolated rocky shores |
| Eastern curlew *Numemius madagascariensis*) | Widespread on intertidal mudflats | Rare. Non-breeding migrant. Nests in Siberia |

#### Waterbirds

Waterbirds feed on intertidal reefs and mudflats and in freshwater wetlands on islands. Several species, especially herons, breed on GBR islands.

#### Terrestrial birds

Terrestrial bird species biodiversity on GBR islands is lower than the nearby mainland. Of 180 birds recorded from Magnetic Island[118], approximately 50 appear resident[83]. The density of particular species is often higher on the islands than the mainland (eg buff-banded rail, *Gallirallus philippensis*, mangrove golden whistler, *Pachycephala melanura*) (M Turner pers obs). One sub-species, the Capricorn white-eye (*Zosterops lateralis chlorocephala*), is endemic to the Capricorn Bunker Group. The majority of recorded sightings of the nationally critically endangered Dawson yellow chat (*Epthianura crocea macgregori*) are confined to Curtis Island (J Olds pers comm).

Hundreds of thousands of pied imperial pigeons (*Ducula bicolor*) roost and nest on many GBR islands north of Mackay, particularly north of Three Islands[65]. They prefer mangroves on low wooded islands or closed vine forest on continental islands. Each evening in summer the pigeons return to the islands from mainland rainforests depositing droppings containing nutrients and fruit seeds. On Milman Island, about 70 percent of the plant species were assisted to the island by pied imperial pigeons[20].

### *20.1.3.3 Terrestrial invertebrates*

Islands of the GBR support a diverse array of invertebrates including pseudoscorpions, mites, spiders, centipedes, isopods from twenty order of 109 insect famililies[78]. Like other fauna, the assemblages of invertebrate fauna on the islands are likely to be similar to those in equivalent mainland habitats but with some differences due to island zoogeography.

Island invertebrates are highly dependent on habitat. Some species such as scale insects on the pisonia of Tryon and Wilson Islands in the Capricorn Bunker Group have caused damaging effects on island vegetation[64,88].

Up to 118 species of butterfly have been recorded for GBR islands including two endemic species (Table 20.2)[113]. Island isolation may contribute to the rapid speciation of butterflies. Butterfly distribution depends on the distribution of host plants for larval feeding. Several islands are dry season (winter) aggregation refuges for some butterfly and moth species, especially from family Nyphalidae[114] (M Turner pers obs).

### *20.1.3.4 Freshwater wetlands fauna*

Of all of the GBR islands, Hinchinbrook Island has by far the greatest number of freshwater wetlands, including permanent wetlands, and the best representation of aquatic fauna. Twenty-eight species of freshwater fish have been recorded in the freshwater habitats of Hinchinbrook Island, including the jungle perch (*Kuhlia rupestris*)[77]. All fish species surveyed on Hinchinbrook Island have also been recorded in adjacent mainland wet tropical freshwater habitats.

At least seven species of frog have been recorded on islands of the GBR although this is probably an underestimate[111]. Frogs and many aquatic invertebrates are adapted for life in ephemeral wetlands and perennial freshwater stream habitats on the islands.

## 20.2 Vulnerability of Great Barrier Reef islands to climate change

Predictions of the potential impacts of climate change on island terrestrial flora and fauna are not certain. Most of our assumptions for determining vulnerabilities are based on our observations, case studies and literature reviews, bearing in mind that the current knowledge of flora and fauna on GBR islands is fragmented and incomplete. Figures 20.2 and 20.3 depict potential changes to GBR islands in association with climate change.

***Figure 20.2*** *Potential impacts on continental islands based on climate change projections for the GBR*

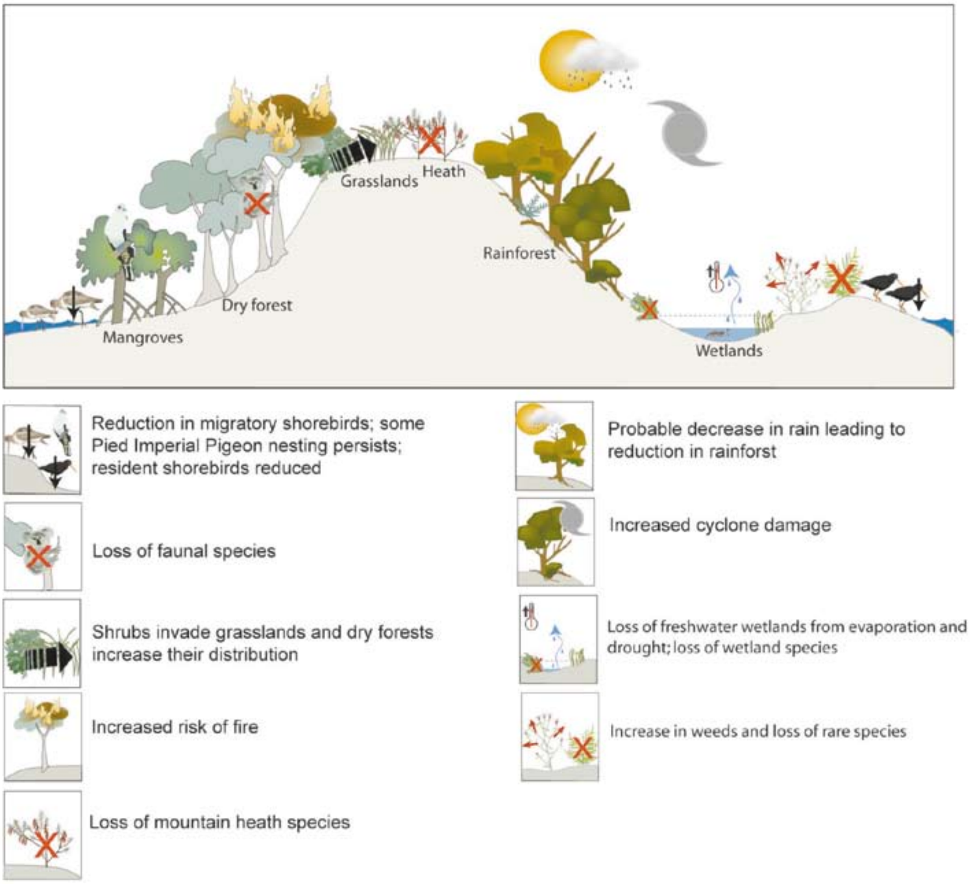
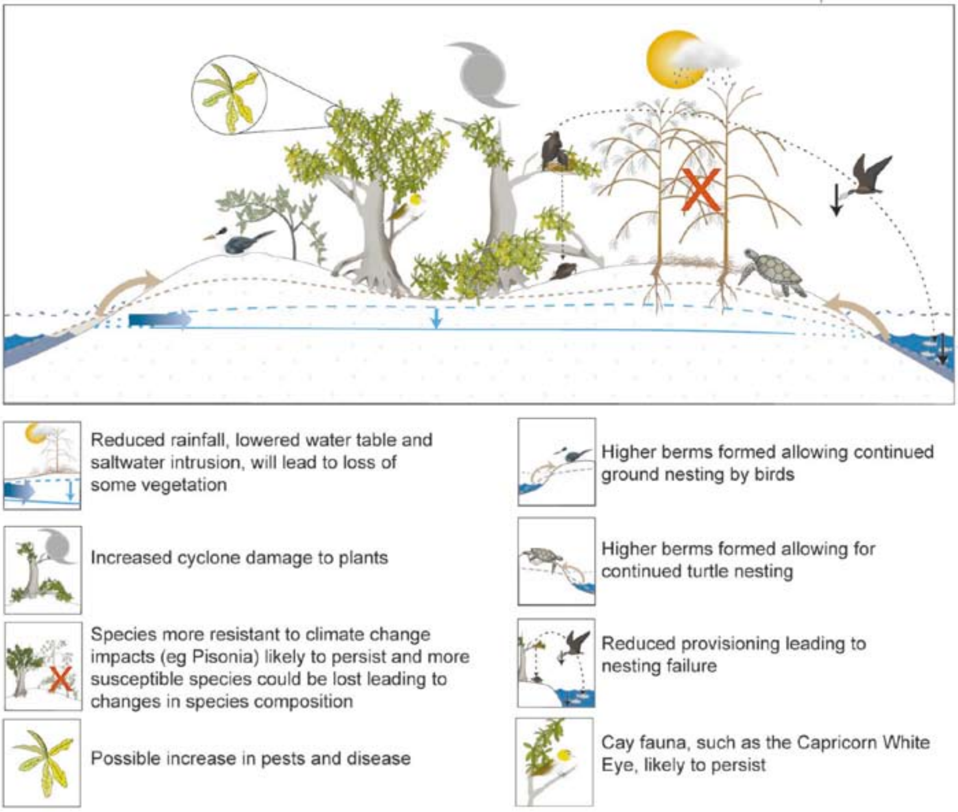


***Figure 20.3*** *Potential impacts on coral cays and low islands based on climate change projections for the GBR*



## 20.2.1 Changes in El Niño Southern Oscillation and ocean circulation

The major direct impacts of El Niño-Southern Oscillation (ENSO) events on islands are from changes in rainfall and tropical storm severity and frequency. These are discussed in sections 20.2.6 and 20.2.7. Changes to Enso and ocean circulation may also lead to changes in ocean productivity, which affects seabird food availability, and may affect their current impacts on island vegetation. This section discusses the effect of changes in ocean currents on plant colonisation of islands.

### *20.2.2.1 Impact – changing ocean currents*

Cays and low wooded islands form on reef flats as unvegetated low sand banks and are colonised by pioneer plants. Many of these plants are transients that may never succeed as permanent residents but help to develop cay soils and provide better habitat for other colonising plants[49]. Waterborne dispersal is a common method of colonisation of islands by terrestrial plants[28,105,86], even for islands where birds bring many seeds. On Masthead Island in the Capricorn-Bunker Group, 52 percent of 40 plant species are ocean dispersed[7]. In particular, many plant species favouring the supra-littoral zones of sandy and rubble shores produce buoyant seeds, and most mangrove species have buoyant

propagules[49,105,47]. Shores of islands are dynamic, providing bare ground for colonising plants[86]. Sea currents carry seeds long distances to islands from mainland Australia, Papua New Guinea, other GBR islands and islands in the Pacific[20,47]. Most of the drift propagules reaching the Swains Reef cays for instance, come from the New Caledonia, Vanuatu and Fiji region[105].

Although local currents around islands are principally the result of winds and tides, ocean currents can have an affect. If the direction or speed of ocean currents is altered by climate change the number of seeds from the Pacific arriving on GBR island beaches may increase or decrease. Any change may alter the species composition of island seashore vegetation.

### 20.2.2 Changes in air and water temperature

Increases in air and sea temperature are two of the more predictable alterations that will occur with climate change (Lough chapter 2). Air temperature increases will have direct and immediate impacts on island flora and fauna, as will the temperature of freshwater wetlands. Islands have little direct exposure and sensitivity to sea surface temperature but may be impacted indirectly. Each of these temperature increases is discussed below.

#### *20.2.2.1 Impact 1 – increase in air temperature*

Terrestrial flora and fauna live in climatic conditions that are often determined by air temperature and rainfall. Temperature can have a direct impact on organism functions and can also affect evaporation rates and moisture content of plant tissues. Warmer air temperatures compound the effects of lower rainfall and increased droughts (discussed in section 20.2.7.1).

##### Increase in air temperature: flora

Increased temperatures will favour some plant species and disadvantage others. For example, some tropical and semi-arid species will be advantaged and able to colonise new habitats at higher latitudes or higher altitudes as the air temperature and habitats warm[84].

Higher temperatures improve photosynthesis, with peak productivity in tropical plants at 27°C under optimal light conditions[70]. However, for plants growing under less than optimal light conditions, such as in the shade or under frequent cloud cover, the impact of temperature on photosynthesis is less pronounced[70]. As a result, local weather conditions of cloudiness and shading by the forest canopy may be important factors in the responses of plants to increased temperatures.

Higher air temperature may increase evaporation rates making less water available to plants, thus favouring CAM plants that are adapted to dry conditions[70,126]. Higher temperatures may also increase the rate of transpiration of water from plant foliage. The result is increased water stress on plants. Frequent droughts may also change the composition of tropical species by favouring the more resilient drought-tolerant species of deciduous and deeper rooted tree plants[84].

In the open vegetation, other species which are more adapted to water stress, including grasses, succulents, herbs, hardy shrubs such as the grass trees (*Xanthorrhoea* spp.) and other woody sclerophyll species such as eucalypts, acacias and casuarinas, will most likely be favoured with increased evaporation. On the islands of the GBR, climatic changes could lead to a gradual

replacement of rainforest by eucalypt and acacia woodlands, and a replacement of shrubs by short-lived herbaceous plants including grasses.

Warmer air temperatures increase fire risk, especially if there is an increase in the number of very hot days[119]. Higher temperatures reduce the moisture content of plant leaves and stems making them more susceptible to fire. More frequent and severe fires will favour some of the most common open-forest species now growing on the islands. The fire resistant $C_3$ woody plants such as the acacias may increase in many areas at the expense of herbaceous species. The fate of grasslands on the GBR islands is difficult to speculate. We suspect that some grasslands are already challenged by invasive $C_3$ plants such as *Xanthorrhoea* spp., eucalypts, casuarinas and acacias. However, under frequent fire conditions some grasslands are likely to increase in area at the expense of closed-scrubland. Much depends on the response of the grass species to changing conditions.

Hilbert[52] and Williams and Hilbert[121] have suggested that lowland mesophyll vine forests (a rainforest type) that occur on the mainland and continental islands adjacent to the Wet Tropics World Heritage Area may be at an advantage through an increase in temperature, and could increase in area. However, this will only occur if rainfall and light intensity is adequate[52,70]. Rainfall, not temperature, is the main determinant of rainforest distribution[53].

In a warmer climate, weeds and other invasive plants appear to be at an advantage thus creating the potential for dominance[31]. According to Richard Clarkson (pers comm), higher temperatures will assist lantana growth. All plants affected by temperature or water stress are more susceptible to attacks by pests and diseases such as insects, fungi and viruses[79,10].

The latitudinal distribution of flora along the length of the GBR is influenced by tropical conditions such as the temperature and day length, which mirrors plant distribution on the mainland. As air temperature increases some cooler climate species may not flourish and their distribution will shrink southward. Examples from the Keppel Group are the swamp mahogany (*Eucalyptus robusta*), now occurring on Great Keppel Island at its northern limit of natural distribution, and the lemon scented gum (*Corymbia citriodora*) open-forests on North Keppel Island. Both may be lost from the GBR due to warmer temperatures and drier conditions. Local extinction of eucalypts and reduction of acacia species has already occurred on small islands such as Prudhoe Island in the Whitsunday Group and Palfrey Island, near Lizard Island in the far northern GBR. Other species tolerant of higher temperatures that are more common in the northern GBR may spread further south. For example, tropical seashore plants such as *Pemphis acidula*, wongai plum (*Manilkara kauki*) and *Pouteria obovata* may expand from northern cays and establish on southern coral cays if dispersal processes are still operating.

Altitudinal retreat and extinction of flora and fauna has been predicted for mountains of the Queensland Wet Tropics as temperature rises[122]. There is little altitudinal variation on GBR islands, except for Hinchinbrook Island. At 1142 metres, Mt Bowen is the highest of several peaks on Hinchinbrook that, with cooler temperatures and cloud moisture, supports montane banksia heaths, rainforest patches and several species of localised orchids (W Lavarack pers comm). With a general rise in temperature and light, the mountains will become unsuitable habitat and the banksia heaths and orchids may be lost.

### Increase in air temperature: invertebrate fauna

An increase in air temperature, especially a rise in minimum temperatures, may allow cold sensitive invertebrates to expand their ranges. An increase in air temperature may also speed up metabolic rates of insects and other invertebrates and lead to shortened life cycles. For example, herbivorous grasshoppers that reproduce each summer on Raine Island may be able to produce more generations each summer, rather than the current one or two generations (G Batianoff pers obs).

Higher temperatures may be speeding up the metabolic rate of the scale insect, which increased to outbreak proportions on Tryon and Wilson Islands, Capricorn Bunker Group in 2006[12]. No link has been made between scale insect outbreaks and climate change in this case but the potential for native and introduced invertebrates to rapidly increase in population is greater with higher temperatures. Of course there is also the potential for warmer temperatures to speed up the life cycle of the scale insect's main predators: ladybird beetles and parasitic wasps.

One observed consequence of faster insect development relates to pollinator species. Adult population pollinator levels may no longer peak when appropriate flowers are at their most abundant. This could disadvantage both the plants requiring pollination and the insect pollinators requiring nectar.

The distribution of butterflies is likely to alter with increased temperatures. The results of BIOCLIM modelling of Australian butterflies in general shows a rise in temperature of 0.8 to 1.4°C will cause a distribution decrease for 88 percent of the species. With an increase of 2.1 to 3.9°C, 92 percent of species will have a decreased distribution, with 83 percent experiencing distribution shrinkage of greater than 50 percent[13]. The capacity of butterflies to change their range is highly dependent on their host plants. The species most likely to survive will have the ability to range over large distances and rely on food plant species that occur in many climate zones. Other butterflies are much more restricted and will have little capacity to move. The lycaenids, such as the endemic species in the Whitsundays Islands, have limited capacity to disperse if temperatures rise[68] and will probably disappear under these conditions.

Most butterflies rely on vegetation for food during their caterpillar stage. If higher temperatures dry the foliage, increase fire risk or cause the habitat to evolve to be more sclerophyllous, some species of foliage feeding butterflies will be advantaged and others disadvantaged. The food plants of butterflies and other herbivorous insects may become too dry or their food plants may disappear from an island, which could lead to local extinction of the butterfly.

### Increase in air temperature: vertebrate fauna

The effects of higher temperatures on vertebrate fauna distribution will follow a similar pattern to flora and plant eating invertebrates, especially for species closely tied to particular habitats. Some fauna will move in response to increased temperatures, depending on their sensitivity to climate change, their mobility, life span and availability of key needs[102]. Others cannot cross the ocean to alternative sites.

Water requirements for animals increase as temperatures rise, and individual animals may suffer heat and water stress. For example shorebirds and seabirds nesting on open ground during summer are already exposed to high temperatures and any increase may affect their capacity to keep themselves and their chicks cool.

Williams and Hilbert[121] predict that in the tropical rainforests of the Wet Tropics of Queensland the most vulnerable species are at higher elevation locations while lowland species such as most of those on GBR islands will be less affected. If lowland tropical rainforest areas of GBR islands and adjacent mainland do increase as suggested above, birds that favour that habitat may increase[104].

The higher temperatures that shift tropical conditions and fauna species further south will also cause sub-tropical ecosystems and their fauna to contract to the south. Species currently at the northern limit of their range on GBR islands may be lost from the GBR. Not all changes may be detrimental. The red fox (*Vulpes vulpes*) is an introduced pest, which has serious adverse impacts on Australian wildlife[45]. Currently the only GBR island with foxes is Curtis Island, where it predates on turtle nests (J Cruise pers comm). Foxes do not like tropical humid conditions[124]. Increasing temperatures, especially if humidity is also increases, may weaken the existing population and lessen the chances of it colonising other islands.

Any change to insect life cycles can also affect their competitors and predators[115]. For example, the timing of terrestrial bird nesting often coincides with times when insects are abundant to provide food for chicks. If insect life cycles change because of increased metabolic rates, the birds' food supply may not be available at this critical time[125,22]. In addition, temperature is a major cue for the timing of short distance bird migrations[19]. Migration is discussed further in section 20.3.

#### Increase in air temperature: animal diseases

Considerable attention has been focused on the potential spread of diseases of humans and livestock under a climate change scenario[38,36]. Temperature rises may trigger dormant stages of diseases, and increased heat and water stress on animals may increase their susceptibility to disease[48]. Tropical diseases may widen their distribution as tropical conditions spread further south from the equator. For example, the spread of West Nile disease in the United States of America is linked to warmer temperatures[35]. Avian malaria and avian pox in Hawaii are predicted to spread as their mosquito vector expands its range and capacity with warmer temperatures[48]. While these diseases are not currently present in Australia, they demonstrate how temperature can increase the impacts of indigenous or introduced diseases.

One study that demonstrates the climate change impacts of diseases involves the chrytid fungi disease that is devastating frog species worldwide. The impact is being driven by temperature increases[95]. In the American tropics, 67 percent of *Atelopus* frogs have declined or vanished. Some frogs most vulnerable to the disease include those living in the highlands of north Queensland. Extinctions of frog species worldwide (122 species possibly extinct), including Queensland species, demonstrate the limited adaptive capacity of frogs to the disease effects of climate change. Increased temperatures may increase the virulence of chrytid disease in frogs on the mountains of Hinchinbrook Island. The vulnerability of flora and fauna to existing or new diseases is not well known but, as demonstrated by the frog extinctions, the consequences may be very high.

### *20.2.2.2 Impact 2 – increase in water temperature of freshwater wetlands*

Increased air temperature will raise the water temperature of freshwater wetlands and increase evaporation rates. Freshwater habitats on islands vary with location and tend to be ephemeral, shallow and dynamic with many having limited species richness. Plant and animal species in small water bodies tend to have high tolerances to short-term temperature fluctuations. However there are limits to their tolerance, and higher water temperatures may lower the capacity of aquatic life to obtain food or reproduce.

Some freshwater fishes of GBR islands, particularly freshwater jungle perch, rainbow fish (Melanotaeniidae) and blue-eyes (Pseudomugilidae) are vulnerable to increased water temperature. Jungle perch on Hinchinbrook Island favour deeper pools in hillsides of permanent streams. As water temperatures increase, the thermal tolerance threshold of jungle perch is likely to be exceeded; however the exact threshold is unknown.

Fauna, including frogs and many invertebrates, that must complete their life cycles in ephemeral wetlands are vulnerable if ephemeral wetlands evaporate at a faster rate than at present.

Some species may be able to adapt to increased water temperature, as increased temperatures will favour individuals with greater thermal tolerances. The capacity for non-flying fauna to move is limited in island freshwater systems since the systems are small and rarely interconnected. Recruitment to freshwater wetlands on islands has all of the challenges of freshwater wetlands on the mainland but with the additional barrier of the sea. Freshwater habitats are likely to become less diverse, with fewer species.

A decline in wetlands will affect the eastern water rat (*Hydromys chrysogaster*) that relies on wetlands for food and nesting sites although it can live and migrate through saltwater wetlands.

Waterbirds can move from island wetlands to mainland wetlands as the island wetlands decline. The future of most waterbird species depends more on what happens to wetlands on mainland Australia than what happens on the small part of their range on islands.

#### *20.2.2.3 Impact 3 – increases in sea surface temperature*

The impacts of increases in sea surface temperature on island flora and fauna are indirect. Increases in sea surface temperature will kill coral and other calcium-accumulating organisms (eg algae) and their skeletons will break down into rubble and sand, providing a short-term increase in island building materials, particularly for cays on the windward side of reefs (Smithers et al. chapter 21). Colonisation by plants tolerant of the alkaline fresh rubble (pH greater than 8) is likely to follow. However, the death of calcium-accumulating organisms, such as corals, will eventually reduce the supply of sand and rubble available for island building (Hoegh-Guldberg et al. chapter 10).

Increased sea surface temperature impacts seabird feeding (Congdon et al. chapter 14) reducing the nutrients seabird guano contributes to island plants.

### 20.2.3 Changes in atmospheric and ocean chemistry

Island habitats in the GBR will be directly impacted by atmospheric increases in carbon dioxide ($CO_2$) concentrations but only indirectly affected by changes in ocean chemistry. These impacts are discussed separately.

### *20.2.3.1 Impact 1 – elevated atmospheric $CO_2$ concentrations*

#### Elevated atmospheric $CO_2$: flora

Carbon dioxide concentration is increasing in the atmosphere (Lough chapter 2). Under current $CO_2$ levels the $C_4$ plants generally have higher $CO_2$-fixation rates than the ancestral $C_3$ plants, giving $C_4$ plants a competitive advantage. In tropical and sub-tropical Africa the competitive advantage of $C_4$ grasses over $C_3$ trees gives as much as 40 percent superiority under a dry climate and low $CO_2$[61]. However, $C_3$ plants can survive droughts by adaptations such as reducing leaf area and/or loss of leaves during dry periods[27].

Increases in atmospheric $CO_2$ will increase the growth rates of many plants, thus driving vegetation dynamics at a more rapid rate. For $C_3$ plants, an increase in $CO_2$ concentrations will generally enhance photosynthesis, stimulate additional plant growth and increase the carbon to nitrogen ratio in plant tissues[85,84]. Most importantly, this will provide a competitive advantage for $C_3$ plants over $C_4$ grasslands[31,76]. According to Bond and Midgley[15], the effects of elevated $CO_2$ may already be contributing to tree invasions and the thickening of woody vegetation within tropical grasslands. Observed invasions of woody vegetation into mainland Queensland grasslands that are occurring despite frequent burning[37] may be partly explained by elevated $CO_2$. In the same way, the grasslands of the GBR islands would also be vulnerable to the impact of elevated atmospheric $CO_2$. Weed invasion is also favoured by the enhanced $C_3$ plants[127].

According to Long and Drake[75] the combination of elevated $CO_2$ and temperature will stimulate photosynthesis in low light such as in understorey trees and shrubs.

As $CO_2$ increases, stomatal conductance reduces so the effective water consumption of plants improves[93]. The increase in water use efficiency may offset the effects of elevated temperatures and lower rainfall (ie the effect of drought may be ameliorated). If the concentration of $CO_2$ doubles in the next 50 years as predicted, an improvement in water efficiency will offset a 10 percent decrease in rainfall[93]. This presumes that other factors such as adequate nutrients are not inhibiting growth. Vegetation on some coral cays that receive nitrogen from bird guano, will respond well. However, vegetation on nutrient poor islands, such as young cays and granitic-based continental islands will be less likely to respond unless they are nitrogen fixers which are highly responsive to increased $CO_2$ levels[94]. Under these scenarios habitats may be structurally similar but have a different species composition.

#### Elevated atmospheric $CO_2$: wetlands

A higher $CO_2$ gas level favours the growth of mangroves if salinity is low[4]. Mangroves may therefore expand into brackish and freshwater wetlands (Lovelock and Ellison, chapter 9) including those on islands.

#### Elevated atmospheric $CO_2$: fauna

Elevated $CO_2$ will probably have little effect on the respiration of fauna due to their ability to adapt and/or survive under relatively high $CO_2$ levels. Current and expected atmospheric $CO_2$ levels are in the order of hundreds of parts per million[59] (Lough chapter 2). Currently humans survive in submarines with 9000 parts per million, bees survive in hives with 30,000 parts per million, and termite mounds and mammal burrows may have 50,000 parts per million[123,46].

Increased leaf growth due to increased concentrations of $CO_2$ means that the ratio of carbon to nitrogen in the leaf is altered. Plants grown at increased concentrations of $CO_2$ have reduced amounts of nitrogen[63] and are less nutritious for folivores, including possums and insects. The leaves of these plants are also tougher and contain more concentrated defence compounds[72]. Koalas on Magnetic Island will be impacted since they already eat and digest large amounts of leaves to obtain adequate nutrition. A decrease in the nutritional value of leaves will force koalas to eat more leaves to get the same total amount of nitrogen. For such a species, on the edge of its range, any additional survival stress such as poorer quality leaves may lead to local extinctions.

Leaf-eating insects are important parts of many food chains. If these insects decrease in abundance or vigour due to decreased leaf quality, the predators of the insects will also be impacted. Conversely, some plant pest invertebrates may increase in abundance with rising $CO_2$ concentrations[62].

#### *20.2.3.2 Impact 2 – ocean acidification*

The sea is projected to become more acidic (Lough chapter 2). Increased acidity of ocean waters may affect the ability of marine life to accumulate calcium carbonate (Hoegh-Guldberg et al. chapter 10), and decrease the long-term supply of sand and rubble building materials for cays and sand islands. Increased acidity may also decrease the formation of stabilising beach rock on cays and sandy beaches placing the islands at greater risk of erosion (Smithers et al. chapter 21).

### 20.2.4 Changes in light and ultraviolet radiation

Little change is expected in light and ultra violet-B (UVB) levels for terrestrial ecosystems in tropical areas such as the GBR (Lough chapter 2). Any small increase in UVB and light levels may have some small effect on flora of islands in the GBR. A larger impact may be from the combined effects of elevated $CO_2$ and temperature, which stimulates photosynthesis in low light[75]. Some understorey and ground cover plants growing in the shade may grow faster.

### 20.2.5 Sea level rise

Sea levels on the GBR are expected to rise gradually by 0.1 to 0.9 metres by the year 2100 (Lough chapter 2). There is also a risk of a catastrophic rise if the Greenland or West Antarctic Ice Sheets collapse[59].

The potential impacts of sea level rise on GBR islands and cays can be summarised as (adapted from Smithers et al. chapter 21):

- General short-term increase in size and number of coral cays and some sand spits with a rise in sea level up to one metre above the present level (maybe 100 years away).
- General inundation and erosion of all islands as sea level rise continues above one metre (beyond 2100) and inundation and erosion of shorelines for many continental islands beginning now.
- Elimination of most coral cays, inshore sand islands and lowland areas of continental islands if there is a catastrophic rise of several metres due to an ice sheet collapsing.

### *20.2.5.1 Impact 1: short-term increase in cays and sand spits*

Coral cays and islands built of sand or mud are often only a few metres above sea level. Some larger sand islands have higher dunes built of windblown sand that may be stabilised by vegetation. Island shores and dunes tend to be dynamic and can adapt to some changes in land profiles[86]. Cays can migrate across reef flats under a process of accumulation of sand on one side and erosion on the opposite. Most continental islands are predominantly rock but many have sandy beaches and lowland areas of accumulated sands.

With a rise in sea level below one metre, increased wave action will mobilise offshore sources of sand or sediments to build shores and increase the size of many cays and sand spits, and create new cays (Smithers et al. chapter 21).

#### Short-term increase in cays and spits: flora

An increase in the number and area of cays creates opportunities for colonising plant species that can grow on alkaline sand and coral rubble. On cays that migrate across reef flats, vegetation washed away on the eroded side is replaced by pioneering species on the accumulation side. Colonisation of new cays by plants may take longer and depends on the closeness of the seed source, currents, wind direction and the movement patterns of seabirds and terrestrial birds. Sands deposited to establish new cays or enlarge existing islands will be high in salinity, promoting establishment of salt tolerant seashore plants, including both native species such as saltwater couch (*sporobolur virginicus*) and weed species such as crow's foot grass (*Eleusine indica*). Once established, weeds can invade native vegetation and cause severe impacts on native habitats.

An increase in the area of cays may enlarge the areas available to pisonia closed-forests and other woody species, increasing total area of pisonia closed-forest on islands such as the Capricorn Bunker Cays.

#### Short-term increase in cays and spits: fauna

An increase in the number and area of cays and spits will provide new opportunities for nesting seabirds and turtles. An expansion of woody forests on cays may increase the area of suitable habitat for tree-dependent species of fauna, including the endemic Capricorn white-eye, the pied imperial pigeon, coastal raptors and some seabirds.

Mangroves on low wooded islands and inshore sediment islands may be able to trap sediment and continue growing with an increase in sea level and island heights (Lovelock and Ellison chapter 9). Sediment infilling may provide opportunities for the establishment of rainforest species, especially if pigeons or fruit bats roost and deposit seeds and nutrients on the islands.

#### Short-term increase in cays and spits: freshwater wetlands

An increase in wave energy leading to an increase in berm height (highest part of beach) may help to retain water in some lowland wetlands behind beaches and dunes on sand and continental islands.

### *20.2.5.2 Impact 2 – inundation and erosion from gradual sea level rise*

As sea level gradually rises there will be two major effects, especially at high tides and during storm surges:

i) Inundation.

ii) Erosion of shorelines.

Many continental islands will erode and inundate at even low levels of sea level rise. After a period of cay building there will be a point where offshore sediment supplies are used up and any further sea level rise will begin to erode and inundate cays.

#### Inundation and erosion: freshwater lenses

An increase in sea level may cause an intrusion of saltwater into the freshwater lens within coral cays or islands[18]. The saline contamination of freshwater lenses of smaller islands has already been reported from Pacific islands[60]. Lenses are impacted at their edges and therefore larger cays with a greater area of lens will be affected at a slower rate than smaller cays.

#### Inundation and erosion: cay flora

Some island flora can tolerate short-term inundation with brackish water but not for extended periods. Deep-rooted woody plants, such as some rainforest species, do not survive prolonged saline intrusions. Pisonia closed-forests have special physiological and morphological adaptations to withstand environmental stresses such as drought and seawater inundation and may replace rainforest species. If inundation of freshwater lenses continues, pisonia forest will eventually be replaced by more tolerant arboreal shrubs such as *Abutilon albescens* and *Argusia argentia*, and ground cover plants such as chaff flower (*Achyranthes aspera*), *Boerhavia* spp., moon flower (*Ipomoea macrantha*), stalky grass (*Lepturus repens*), pigweed (*Portulaca oleracea*) and saltwater couch (*Sporobolus virginicus*). These shrubs and grasses will take over as pisonia trees die, creating glades and open sunlit areas. These scenarios have already been observed on Tryon Island, Capricorn Bunker Group[64,10,12].

Vegetation will be lost on eroded shores. The common beach scrub trees such as droopy leaf (*Aglaia elaeagnoidea*), native persimmon (*Diospyros maritime*), native cherry (*Exocarpos latifolius*), *Manilkara kauki* and beach almonds (*Terminalia* spp.) will be displaced and have to relocate to newly formed beach ridges. In many instances these species will be replaced by salt tolerant woody plants such as octopus bush (*Argusia argentea*), coastal she-oak (*Casuarina equisetifolia*), sea trumpet (*Cordia subcordata*), *Guettarda speciosa, Pemphis acidula, Premna serratifolia,* sea lettuce tree (*Scaevola taccada*) and *Suriana maritima*. Salt tolerant seashore plants are likely to expand their range on many islands and form monospecific stands on some islands. Erosion on Heron Island in the Capricorn Bunker Group has resulted in native plants such as the hairy spinifex (*Spinifex sericeus*) no longer re-establishing on the beaches and being replaced by introduced plants such as sea rocket (*Cakile edentula*). *Cakile* also replaced the coral cay littoral margin herb *Trachymene cussonii* in the mid 1990s that formed succulent mats on the beaches along many Capricornia Cays.

According to Heatwole[49] and Batianoff and Naylor[10] vegetation on cays can become unstable due to drought, sea erosion and/or pest damage. Some cays, such as Gannet Cay, one of the Swains Cays, have lost their vegetation altogether in recent years (P O'Neill pers comm). Although this loss cannot

be attributed directly to erosion caused by sea level rise, it is an example of a phenomenon that will become more frequent. Large cays with stable cores, beach or phosphate rock, established soils and large trees, such as Green Island and the Capricorn Bunker cays will be more resistant to erosion than smaller more mobile and less vegetated cays. With continuing sea level rises, exacerbated by periodic cyclones, all cays and their vegetation may eventually disappear.

### Inundation and erosion: continental island flora

New dynamic shorelines on continental islands will be constantly changing as sea level rises and pioneering plants establish and in turn perish away. Vegetation behind the beaches, salt marshes and mangroves will be inundated. In mangrove areas sea level rise will cause mangrove vegetation to expand shoreward (Lovelock and Ellison chapter 9) along the inshore low islands. Salt marsh and brackish wetlands may move inland on large sand islands in the southern GBR, particularly Curtis Island.

### Inundation and erosion: freshwater wetlands

As shorelines erode and low-lying areas of continental islands are inundated, freshwater wetlands will shrink, severely impacting freshwater aquatic fauna, including fish breeding cycles. Most large freshwater animals may disappear from the islands. Only stream habitats of Hinchinbrook Island and a few ephemeral streams and pools on other continental islands are likely to survive the seawater inundation of the lowland wetlands.

### Inundation and erosion: fauna

The nesting habitat of birds that breed above the intertidal zone will be affected by rising sea level. As beaches are eroded away, habitat may be lost and new habitat created. Ground nesting seabirds and shorebirds, such as the beach stone-curlew, the sooty oystercatcher and the red-capped plover (*Charadrius ruficapillus*), frequently select new nesting sites each year. Sudbury Cay was a seabird breeding island until all the vegetation was lost[97]. The unvegetated Gannet Cay in the Swains Cays still supports some species of nesting birds but the numbers and species are less than when it had vegetation cover[97]. A gradual change in sea level and increased erosion will still probably create some beach conditions suitable for shore nesting birds for each breeding season.

Several island bird species will be at risk if their pisonia closed-forest habitat disappears through rising sea level inundation and erosion. On the Capricorn Bunker Cays the Capricorn white-eye will lose its major habitat, black noddies (*Anous minutus*) will no longer have pisonia branches to nest on and wedge-tailed shearwaters (*Puffinus pacificus*) will no longer have pisonia root mass to support their burrows and bare ground to walk on under pisonia trees. On Tryon Island (Capricorn Bunker Group) where pisonia closed-forest was lost through insect attack, shearwater nesting has substantially declined (P O'Neill pers comm). Black noddies can nest on other trees such as casuarina on Lady Elliott Island (B Knuckey pers comm) but their nesting success may be reduced. The more salt tolerant shrubs and grasses that colonise the areas now devoid of pisonia may provide nesting habitat for other seabird species that prefer low vegetation. However there are many islands with shrub and grass vegetation in the GBR but few with pisonia closed-forest, and black noddies and wedge-tailed shearwaters may have few other options for nesting sites[10].

Loss of littoral rainforest and beach sands through inundation will impact fruit pigeons, pied imperial pigeons and other fauna species that use these habitats. Some species will be able to find alternative habitat. Pied imperial pigeons, for example, can also roost in mangroves.

In addition to nesting sites, roosting sites are critical for shorebirds and seabirds. Birds use isolated roosting sites in intertidal areas during the rise and fall of tides and at sites above high tide during the height of the tides. Roosts may be sand spits, sand banks, salt marsh areas or beaches behind mangroves. Roosts where birds can rest safe from most predators and disturbance are very important for the energy balance of shore birds. Any loss or relocation of bird roosting sites due to rising sea level effects will mean shorebirds and seabirds move further from feeding areas, increasing the energy expended by the birds to access food. The option to move to other roosting sites can be compromised in areas densely settled by humans, as the birds require roosting sites with little or no disturbance.

The eventual loss of most coral cays after the initial general increase will have devastating impacts on seabirds and shore birds. There are no nearby continental islands to provide potential alternative nesting sites for birds currently breeding on remote coral cays such as Raine Island, the Swains Cays and the Capricorn Bunker Group. Some seabirds, such as the bridled tern, are able to nest on forested continental islands but the vegetated slopes of most continental islands are not suitable for most seabirds and shorebirds.

Rising sea level will erode away Bramble Cay causing extinction of the Bramble Cay melomys as it is not found elsewhere[73].

The coastal plains habitat of the Dawson yellow chat will be inundated and the landward progression of salt marsh habitat is possible. The impact on the Dawson yellow chat is highly dependent on the future of coastal plains habitat, but as the species is in such low numbers, minor impacts will have catastrophic effects on the species.

The impact of rising sea levels on turtles is discussed in Hamann et al. (chapter 15). Turtles dig up cubic metres of sand when they nest, often churning up vegetation at the top of beaches and creating bare ground favourable for plant colonisation. On very active nesting beaches such as Raine Island no plants can establish during the summer nesting season as the entire area is turned over frequently[47,10]. If the nesting turtle population decreases the foreshores of many islands will be less dynamic and the plant community may shift away from pioneering species to plants favoured by stable soil.

### Inundation and erosion: intertidal mudflats

Intertidal mudflats are important habitats for a range of invertebrates, and as feeding areas for fish at high tide and for shorebirds at low tide. Sea level change is likely to be an important influence on intertidal habitats. Resident shorebirds that breed on GBR Islands, in particular beach stone-curlews, are at risk if key mudflats are inundated. Migratory shorebirds are also at risk (see section 20.4.1).

### Inundation and erosion: rocky intertidal

Intertidal rocky reef communities are highly dependent on tides to provide moisture, food and oxygen. Plants and animals are distributed on the rocks depending on their ability to survive the periods they are covered by sea water or exposed to the air. Some species such as many molluscs and echinoderms are mobile while others including algae, barnacles and oysters are fixed on the rocks[34]. Rocky intertidal

communities are accustomed to living in a dynamic environment. Sea level rise will affect species fixed to the rocks as some individuals at the lower end of their distribution will be disadvantaged and will be swamped. Individuals on the landward side may be advantaged, and colonies of organisms will migrate up the rocks. Individuals of mobile species will be able to move landward if there is suitable similar substrate landward. Species in intertidal rock pools have less capacity to adapt as the formation of rock pools is a long-term process too slow for the predicted rate of sea level rise.

#### *20.2.5.3 Impact 3 – elimination of low islands by a catastrophic sea level rise*

A dangerous climate change event would occur if either the West Antarctica or Greenland Ice Sheets collapsed[92] (Lough chapter 2). The risk of this occurring has not been quantified but if the Greenland Ice Sheet was eliminated the sea level worldwide would quickly rise approximately seven metres[59].

A sudden inundation of several metres will eliminate all coral cays, inshore sand and mud islands and beaches, and lowland areas of continental islands. The impacts on the flora and fauna described in the section above will occur but much faster and with very little capacity for adjustment. Nesting and roosting sites of most GBR seabirds, shorebirds and turtles will be destroyed and intertidal feeding sites submerged.

If sea level eventually stabilises, new beaches will form on continental islands providing nesting habitat for birds and turtles that have survived.

### 20.2.6 Physical disturbances – tropical storms

Winds and waves of tropical storms can severely impact island habitats. Tropical cyclones are predicted to increase in magnitude, but it is not certain if frequency will change (Lough chapter 2). This section discusses the effects of waves and winds. The impact of heavy rainfall events will be discussed in section 20.2.7.

#### *20.2.6.1 Impact 1 – storm waves*

With the prediction of increased extreme events such as cyclones and storm surges, some GBR low islands will be subjected to periodic floodwater and/or inundation by saltwater. Storm waves can erode shorelines but can also build shorelines if they come from certain directions and sources of sand or rubble are available. Cays have been known to 'move' during storm events as sand is eroded from one side and deposited on another. Storms also threaten to inundate and contaminate freshwater lenses[5].

##### Storm waves: flora

Waves can physically damage vegetation, particularly during storm events when waves often carry sand and rubble. Hardy shoreline species, such as *Scaevola taccada* and *Argusia argentea*, succulent herbs, and grasses can be advantaged by storm events over more fragile species. The loss of salt sensitive trees and shrubs, especially rainforest species, will limit canopy biodiversity of many coral cays, particularly in the northern region. However some salt tolerant woody plants such as *Argusia argentea, Casuarina equisetifolia, Cordia subcordata, Guettarda speciosa, Pemphis acidula, Premna serratifolia, Scaevola taccada* and *Suriana maritima*; may expand their range and on some GBR islands. Short-term inundation will have little or no affect on pisonia closed-forests.

Sand formations on continental islands are vulnerable to storm waves, particularly sand spits and barriers, which are often unstable and change shape and size naturally. Vegetation growing on these formations is therefore at risk from storm waves. The unusual dune vegetation growing on a ten kilometre long and narrow dune barrier at Hinchinbrook Island is one site at risk (R Cumming pers comm). The dune barrier separates an ocean beach from the extensive mangroves in the sheltered waters of Missionary Bay. Wave impacts during a cyclone could cut through the barrier, especially at its lowest point. Ocean waves could quickly open up a channel causing extensive damage to the dune vegetation. If the channel persists, there may be major negative impacts to the mangrove forests of Missionary Bay. Similar vegetation types at risk from storm waves in the GBR include dune flora at Whitehaven Beach on Whitsunday Island, and on the sand islands in the southern GBR, such as Curtis and Facing Islands.

Wave damage may create open bare ground providing new opportunities for pioneering native plants and invasive weed species.

### Storm waves: fauna

Ground nesting seabirds and shorebirds are at risk from tropical storms. Waves can drown or smother eggs and young or destroy vegetation and nests. In 1999 a cyclone completely buried most nests of breeding terns on Michaelmas Cay and one episode of seabird breeding was completely destroyed (M Short pers comm). Eighty per cent of the vegetation was buried with most covered by 20 centimetres of sand. After the storm, vegetation slowly grew through the sand or sprouted from seed and many adult birds came back to re-nest on top of the deposited sediments. Within 11 days, 72 percent of adults had returned and were re-nesting. The island was replenished at a higher level but at the cost of a breeding event. De'ath[30] analysed the effect of four cyclones at Michaelmas Cay and determined that long-term average breeding effort was not significantly impacted by these storms. However with cyclones predicted to increase in intensity with climate change, the impact on sand movement, vegetation loss and bird breeding success is likely to increase.

Other fauna impacted by storm waves include turtles whose nests can be eroded or buried during storm events and the Bramble Cay melomys. A severe cyclone may destroy all the vegetation of Bramble Cay, the entire habitat of the Bramble Cay melomys.

## *20.2.6.2 Impact 2 – storm winds*

### Storm winds: flora

Increased severity of cyclones means higher wind speeds and greater damage to vegetation. This was observed during the 2006 category five Cyclone Larry that impacted Dunk Island, the Frankland Islands and the Barnard Islands (G Redenbach pers comm) in the northern GBR. Trees, especially taller specimens, were stripped of leaves and branches and the forest floor was littered with broken plants. Melaleucas in wetlands may topple, snap trunks or drop branches during windy storms. Plant debris from storm winds can dry out and increase the risk of hot fires burning in vegetation such as rainforest and melaleuca swamps that do not normally carry fire.

Recovery of forests from buds or seed can occur but it can take many decades to replace large trees. Higher frequency of storm winds may prevent re-establishment of taller forests. On coral cays, pisonia forests are adapted to shed branches during storms. The fallen trees and/or branches sprout and revegetate the damaged forest areas.

#### Storm winds: fauna

Many birds, mammals, reptiles and invertebrates are killed during cyclones such as Cyclone Larry, but many find shelter and survive (QPWS field staff pers comm). Food may be scarce after a cyclone, particularly for fruit eating fauna. Mobile species, such as fruit bats and birds, can leave islands to seek unaffected forests. Possums, wallabies and rodents are more vulnerable as they cannot leave affected islands. Some tree species, such as figs (*Ficus* spp.) and beach almonds (*Terminalia* spp.), recover and fruit quickly, providing food for the fauna that remain.

Storm winds can impact birds nesting in tree branches, to the point of blowing eggs and chicks out of nests. Damage to trees may affect future nesting opportunities with birds settling for less optimal conditions that may in turn lower the number of successfully fledged chicks. A severe cyclone in the Capricorn Bunker group may adversely impact part or all the habitat of the Capricorn white-eye. Decreases in rainforest species will impact on fruit pigeons and other fauna that rely on rainforests for food and shelter. Pied imperial pigeons may move to mangrove forests to nest and roost if favoured rainforest is impacted.

### 20.2.7 Rainfall and river flood plumes

Rainfall is a critical factor in island ecology and any change will impact directly on island flora and faunal species richness. Rainfall provides water to plant roots near the soil surface and replenishes sub surface reservoirs, including the freshwater lens of coral cays and ground water on continental islands. Plant distribution is determined by a number of factors, including temperature and soil, but moisture availability is a key factor[107,108].

Rainfall predictions under climate change for the GBR are not certain. More intensive ENSO events may have an effect on rainfall. Rainfall may increase in some places and decrease in others. Most likely there will be more intense rainfall events with longer periods of low rainfall or drought in between (Lough chapter 2). Without certainty on rainfall we have examined two scenarios:

i) Generally drier conditions caused by a decrease in the average rainfall or longer periods of drought

ii) Generally wetter conditions due to an increase in average rainfall or episodes of flooding rains

#### *20.2.7.1 Impact 1 – drier conditions*

Many of the effects of drier conditions are similar to or compound the effects of increased air temperature discussed in 20.2.2.1.

### Drier conditions: flora

Without considering other factors, a decrease in average rainfall or decreased frequency of rainfall events will increase water stress in many plants. These plants would have reduced growth and lose leaves. Species susceptible to water stress would not compete successfully with species that have access to permanent water tables, water lenses or have water storage systems (succulent leaves, root storages). This will lead to changes in the distribution of plant species, and the composition of vegetation communities and their fauna.

As discussed in section 20.2.3.1, an increase in $CO_2$ improves the efficiency of plant metabolism so plants require less water. This may help plants compensate for lower rainfall conditions. However, improved efficiency requires adequate availability of nutrients, which are generally lacking on some continental islands and cays of the GBR, except those with many nesting bird colonies.

With a decrease in average rainfall, freshwater lenses are likely to shrink and contract from the outer edges of islands to be replaced with brackish water. Drought on North Tarawa atolls in the central Pacific caused freshwater wells to become saline progressively from the shore towards the centre of the island (M Turner pers obs). Salt tolerant species such as *Argusia Pemphis* and *Scaevola* are advantaged progressively as the freshwater lens shrinks.

One of the harshest environments for plants in the GBR is cays that are too small to have a freshwater lens (islands less than about 60 metres diameter). Plants rely on rain for water as the sand has little moisture-holding capacity and saltwater permeates through the sandy base of the cay. Only grasses and low shrubs are able to grow on these cays. Although the vegetation on such cays is very hardy, a decreased frequency of rainfall is likely to lead to its decline.

### Drier conditions: rainforest

Leaving aside the effect of increased $CO_2$, the effect of decreased rainfall on rainforest patches on GBR islands would be increased water stress. According to Kleidon and Lorenz[69] under these drier conditions forest structures may change, with greater selection for deeper rooting or deciduous species. Evergreen species would then be replaced with more deciduous or structurally shorter ‘dry rainforest’ species or sclerophyll species such as eucalypts, casuarinas and acacias. Island rainforests with access to more permanent water sources, such as a freshwater lens, permanent underground water, stream courses or wetlands, will be more resilient to decreased rainfall. Although, without sufficient rains, these underground sources may not be adequately replenished.

Moisture provided by low cloud cover is an important source of water for plants on the mountains of the Wet Tropics, particularly in the dry season. Climate modelling has predicted that with a doubling of $CO_2$ the cloud base will be shifted upwards by several hundred metres on tropical mountains[52]. Plant species of mountain top rainforest and montane heath have little ability to extend their ranges and will die out. They include orchids, such as the oak orchid (*Dendrobium jonesii*) that grows in the clouds on top of Mount Cook on Magnetic Island and several species which grow in rainforest pockets above 700 metres in altitude on the mountains of Hinchinbrook Island: *Bulbophyllum shepherdii, B. baileyi, B. johnsonii, B. lilianae, B. macphersonii, Dendrobium adae, D. jonesii,* and wedge tip yellow rock orchid (*Liparis angustilabris*) (W Lavarack pers comm). Temperature increases will compound the loss of mountain top species (see section 20.2.2.1).

### Drier conditions: grasslands

Grasslands thrive in conditions of fire and adequate water. According to Bond and Midgley[15] woody resprouters stimulated by elevated $CO_2$ and fire may fundamentally replace herbaceous grassland communities. On GBR continental islands monospecific stands of acacias and other fire resistant woody species are common. We speculate that $C_3$ woody plants may invade and potentially replace many of our current grasslands under fire regimes that favour woody plants, particularly some of the eucalypts and acacias that have lignotubers and/or epicormic buds. However, during prolonged droughts all woody plants are susceptible to dieback, with dead branches creating a greater fuel load, causing hot fires to be hotter and favouring grasslands to replace shrubs.

### Drier conditions: freshwater wetlands

Lower average rainfall will adversely affect freshwater wetlands. Many wetlands on islands are small and ephemeral and it would only take a small decrease in water input to compromise their viability. Less water means ephemeral wetlands will dry for longer periods. This will be exacerbated by an increase in evaporation due to increased air temperature. Aquatic freshwater invertebrates, frogs and fish may not have sufficient water or time to complete their seasonal aquatic breeding cycles in ephemeral wetlands. Of particular interest is the possible impact on the big-clawed shrimp (*Macrobrachium rosenbergi*) that inhabits sub-surface ephemeral streams above the northern beaches of Magnetic Island (D Savage pers comm). A drought event on Magnetic Island illustrated the plight of brackish water fauna. An open pool was isolated from the sea and dried out. In this case, trapped fish were netted by Queensland Parks and Wildlife Service and re-located to a safer site (M Turner pers obs). Although drying events are natural, their frequency and magnitude is likely to increase with less rainfall or longer droughts.

With lower average rainfall, larger freshwater wetlands may shrink, leading to a succession of vegetation from wetland to terrestrial species. Open water and wetland vegetation will be replaced by melaleuca trees, which will be replaced by rainforest gallery vegetation, which in turn will be replaced by eucalypts and wattles.

Most streams on GBR islands and cays are seasonal. With decreases in rainfall amount and frequency, permanent streams on Hinchinbrook Island are likely to have a reduced water volume. This may result in more stagnation in pools, in turn affecting stream invertebrates, frogs and fish. Jungle perch and other freshwater fish will have less habitat and food, compromising the ability of island habitats to maintain viable populations of freshwater fish.

Wetland birds on GBR islands are likely to disperse to mainland sites as island wetlands shrink. Waterbird visitors to GBR islands face many other climate change impacts whilst at mainland sites[89].

### Drier conditions: fire

A general drying of the vegetation from less rainfall and/or droughts will lead to greater fire risk on GBR islands and cays and a shift to fire tolerant species. Many small islands have a limited range of plant species. Their capacity to alter species composition in response to a decrease in water and an increase in fire may be limited. Wetlands, especially on their fringes, are also more susceptible to the increased fire risk due to the drying of foliage.

### Drier conditions: weeds

Declines in the vigour of native plants due to water stress may make them more vulnerable to invasion by weeds that are able to flourish under dry conditions. An increase in fire frequency or severity will also expose bare ground enabling weed establishment and competition with the established native vegetation. This effect may occur on cays and within wetlands, rainforests and sclerophyll woodlands on GBR islands.

One of the greatest risks of weed infestation is in areas of good quality soil currently supporting melaleuca forests or rainforest. If trees are lost to water stress, the extra light and bare soil will allow exotic tropical grass species to establish, as has occurred on Brampton Island (Cumberland Group) and Lindeman Island Whitsunday Group (G Batianoff pers obs). Although not linked to climate change, an example of how weeds can establish on GBR islands if the woody plants are lost is Lady Elliot Island. Humans cleared the plants in this case. At least 40 percent of the island is affected by introduced weedy flora species, including lantana (*Lantana camara*) and *Bryophyllum delagoense*[6], which out-competed coral cayendemic plants such as Trachy and that are unique to the area.

### Drier conditions: fauna

Changes to the moisture content of plants and the species composition and structure of vegetation due to decreased rainfall will have major implications for fauna dependent on vegetation for food and shelter. Rainforest and wetland species will be particularly disadvantaged as their habitat is at greatest risk. Fruit-eating birds and fruit bats will have a reduced food source, particularly since edible fruit suitable for larger animals is already a scarce resource on islands.

The loss of melaleuca trees from wetland areas will disadvantage the large diversity of insects, bats, lorikeets and honeyeaters that feed on nectar and pollen, and the birds and microbats that feed on the insects attracted to the flowers. The rare rusty monitor (*Varanus semiremex*) of the melaleuca wetlands of Magnetic Island is unlikely to have migration options if its habitat is destroyed, and therefore it may become extinct in the GBR.

Changes in vegetation due to decreased rainfall will affect many invertebrate species including butterflies, such as the endemic Whitsunday azure butterfly. The large number of butterflies that use gullies shaded by rainforest tree species as dry season roosts on continental islands will be impacted as increased water stress causes leaf drop in their favoured trees, and there is a vegetation succession to less shady sclerophyll trees.

A decrease in moisture content in leaves may compromise survival of browsing mammals such as possums and wallabies, especially if heat stress from rising temperatures affects them. An increased fire risk may also disadvantage them. Many animals, such as the unadorned rock-wallaby (*Petrogale inornata*) on Magnetic Island, cannot migrate to other islands as vegetation changes. The endangered Proserpine rock-wallaby confined to Gloucester Island, Hayman Island (Whitsunday Group) and a restricted area of the nearby mainland, is at increased extinction risk if there are changes to its vine thicket and beach scrub habitat[87].

Periods of dry conditions do not generally favour soil or herbivorous invertebrates. In rainforests, insect biomass declines during dry periods[42]. If there are longer dry periods, or if ground clouds decrease, there will be fewer soil and leaf litter microbes and invertebrates. Carnivorous fauna feeding in the leaf litter such as skinks, birds and mammals will be adversely affected[120].

Longer dry seasons will also probably affect the life cycle of fruiting plants and decrease the yield of fruit[120]. Fruit eaters including insects, birds and mammals would be adversely affected. This in turn could affect seed dispersal and plant recruitment processes[120].

Although many changes in vegetation due to dry conditions will adversely affect certain fauna species, some species will be favoured. Animals that are more tolerant of water stress and drier habitats will out-compete species with higher water requirements for themselves or their habitat.

### *20.2.7.2 Impact 2 – wetter conditions: increase in average rainfall and/or flood events*

#### Wetter conditions: flora

An increase in rainfall, $CO_2$ and temperature will favour some species of plants and some vegetation types. Rainforest will be supported if rainfall is over 1500 mm, such as on a few inshore continental islands along the wet tropical coast. If average rainfall increases, rainforests may expand into surrounding drier sclerophyll forests. Encroachment of pioneer rainforest species such as rusty pittosporum (*Pittosporum ferrugineum*) onto grasslands may occur, shading out grasses and creating conditions more suitable for rainforest species. Increased rainfall may promote less flammable vegetation and lessen fire risk. On cays, pisonia can tolerate full water lenses and waterlogged conditions better than other woody competitors. Fire and lenses are also discussed in section 20.3.1.

#### Wetter conditions: freshwater wetlands

Wetlands will also be favoured by an increase in average rainfall. Higher rainfall may compensate for increased evaporation caused by higher air temperature. If total rainfall exceeds evaporation, wetlands may increase in size, but there is little room on islands for such an expansion. Soil waterlogging and wetland overflows will have little negative impact on the wetlands of GBR islands. Many wetland fauna species will take advantage of full wetlands for reproduction. Changes in wetlands may provide opportunities for some common invasive wetland weed species such as para grass *Urochloa mutica*.

#### Wetter conditions: erosion and rainfall runoff

An increase in heavy rainfall events will lead to greater surface runoff, sheet erosion and gully erosion. Erosion gullies will expand and sheet erosion may occur on flatter ground. Waterlogged soils will produce more landslips on steep continental islands, a common occurrence on rocky islands with poorly consolidated shallow soils such as Magnetic Island (M Turner pers obs).

Increased runoff from mainland rivers will have little direct impact on most islands although there may be some build-up of sediments on inshore sand and mud islands. Increased runoff may impact reef-building organisms with indirect impacts on the availability of sediments for island building. River runoff can carry individual animals to islands, such as the individual python (Boidae) reported from one island. The arrival of shingle animals on islands, and even enough individuals to begin a population, is more likely if floods increase in frequency or size.

An increase in heavy rainfall events and floods will carry more seeds out to sea from the mainland and inshore islands, therefore increasing the amount of drift seed carried by currents to islands of the GBR[105]. For example, a flood event was observed to deposit large amounts of seed on Raine Island[47]. Seeds and any sprouting plants in the supra-littoral zone on Raine Island are churned over by nesting

turtles, preventing colonisation[11]. Despite these limitations seeds do strike on many islands and new specie may persist if conditions are suitable. There is high turnover of plant species on GBR coral cays with frequent colonisation and extinctions[49].

## 20.3 Interactions and linkages between stressors

### 20.3.1 Interactions

The combined effect of multiple climate change factors may produce a range of possible outcomes on the various island habitats of the GBR. Impacts of changes to one or more climate variable can cause flow-on effects throughout island habitats. Particularly strong interactions will be discussed and other linkages listed.

#### Interactions: fire

Increased fire risk includes an increase in the likelihood of a fire starting and spreading, and an increase in the intensity and size of fires. Fire risk in many island habitats will increase due to higher temperatures[119], a shift to more sclerophyll vegetation and possibly more droughts. A decrease in average rainfall and increased cyclone damage will also increase fire risk.

More frequent and severe fires will favour fire tolerant open-forest species such as eucalypts and acacias over rainforest and wetland species. Eucalypt and acacia communities in turn promote more frequent fires, reinforcing fire effects. Pioneer native species such as casuarinas (*Allocasuarina littoralis*) will colonise ash beds after fire on Keswick Island (Cumberland Group), and Hook Island (Whitsunday Group). *Xanthorrhoea* spp. will be favoured on the Newry Islands and Percy Isles. Grasslands and/or woody vegetation that are favoured by fire and other climatic events are likely to sporadically expand. If higher rainfall episodes are interspersed with droughts the increased growth will dry, creating a greater standing fuel load.

#### Interactions: freshwater lenses

A rise in sea level and lower rainfall will cause the fresh water lenser of cays to shrink. Larger cays will be affected at a slower rate than smaller cays as the lenses are more affected at the edges of islands where saltwater intrudes to replace the shrinking lens. If the average rainfall increases, or heavy rain events are more frequent, the lenses will replenish. Lens changes will affect flora, especially at the islands' margins.

#### Interactions: weeds

Weeds compete with native pioneering vegetation on disturbed ground and can spread into established native vegetation impacting dependant fauna. Increases in number and biomass of weed species are likely with climate change induced effects[32]. Weeds will prosper due to more bare ground exposed by dynamic shorelines, increases in fire frequency or severity, drying of wetlands, and erosion and vegetation damage from storms[55]. Weed invasions of native vegetation will also be enhanced if higher temperature, less rainfall and increases in plant pests stress the current flora. $C_3$ weeds in particular will be favoured more than $C_4$ natives or weeds.

### Interactions: effects of birds on plants

At seabird and pied imperial pigeon nesting colonies, large amounts of soil nutrients are supplied from bird guano, regurgitated food whilst feeding chicks, dead eggs and chicks and occasional dead adult birds killed by disease or misadventure[2]. Some plant species can tolerate or thrive in high nutrient soils. For example, pisonia can utilise nitrogen gained via thin threads of fungal mycorrhizas attached to their roots[103]. Pisonia are favoured over species that cannot tolerate or take advantage of nitrogen rich soil[110]. Climate induced decreases in seabird or pigeon numbers may provide greater opportunity for plants better adapted to lower nutrient levels to out-compete pisonia and others favoured by nutrients. Seabirds also deposit phosphates in their excretions that dissolve in the soil and redeposit as phosphorous rock at about 30 cm depth. The rock helps stabilise the islands and is particularly obvious on Raine Island. This process takes many years so changes due to a decline in seabirds will take decades.

## 20.3.2 Other linkages

Additional linkages between factors that affect island habitats include:

- Increased air temperature, lower rainfall and increased $CO_2$ will affect water stress in island flora and fauna
- Atmospheric $CO_2$ levels, UV light, moisture and nutrient levels will affect photosynthesis and plant growth
- Decreased and/or increased rainfall, rising sea level and higher temperature will combine to impact freshwater wetlands
- Rising sea level and more intense cyclones may build more cays in the short term and/or erode many continental islands
- Changes to either the structure or species composition of island vegetation will greatly impact island fauna
- Productivity changes in foliage, flower and seed production will affect island faunal food chains
- Climate change impacts in other habitats and locations in the world will impact migratory fauna to the GBR
- Changes to water chemistry, water temperature, and rainfall runoff that disrupt calcium-accumulating organisms will impact island formation

## 20.3.3 Constraints to adaptation

The key constraints to adaptation to climate change for most island flora and fauna are probably similar to constraints for mainland species, with some variations for island conditions. A changing environment impacts on both the phenology, which is the way individuals grow and change, and the genetics, which is the way a population of flora or fauna changes its characteristics[101]. Adaptation to a changing climate can take place in three ways:

i) Phenotype adaptation – individuals changing to accommodate a changed environment

ii) Genetic adaptation – a change in the genetic diversity of the population

iii) Migration to more suitable conditions (avoidance/escape)

## Phenotype adaptation

Much of the flora and fauna that colonise newly formed sand or mud islands are opportunistic and have the capacity to survive and adapt to changing environmental circumstances. They often exhibit phenotype plasticity, which is the ability of an organism to express different phenotypes depending on its environment[1,43]. Their genes contain flexibility to allow for physical or behavioural change of individuals. Animals of this type are generalists and are more likely to alter lifestyles and food items to survive, than species with specialised habitat requirements or food items[125]. Phenology is the most responsive aspect of nature to climate change and the simplest to observe[106]. Climate change has already had significant impacts on both plant and animal phenologies in temperate regions, particularly the timing of life cycles induced by temperature[102]. Temperature effects on timing of life cycle are not as obvious in tropical areas because temperatures do not fluctuate as widely between seasons.

Remnant flora and fauna on continental islands were isolated when the islands were cut off from the mainland by rising sea level after the last ice age. Many are unlikely to have the same level of plasticity to adjust to a changing climate as pioneering species on cays and sand islands. There are limits to the adaptability of all individuals and this will vary from species to species. Small islands, with limited area and habitats offer little flexibility for species to change their lifestyles. Eventually the capacity of individuals to adapt runs out and only evolutionary genetic change will allow the survival of a species.

## Genetic adaptation

Genetic adaptation alters some of the characteristics of a population. Individuals who are better adapted to a changing environment will survive and pass on those characteristics to the next generation. The plasticity of a genotype determines how wide a range of genetic variation is in a population[101]. The greater the range of genetic options the more likely a species can adapt. An example of rapid evolutionary change to a climate fluctuation is the annual plant *Brassica rapa*[41]. An abbreviated growing season caused by drought led to the evolution of an earlier onset of flowering in just a few generations . A genetic shift of photoperiodic response by a short generation mosquito showed a detectable adaptive evolutionary (genetic) response over just five years[17]. Species with large population sizes and short generation times are more likely to adapt than species, such as most vertebrates and trees, which have longer generation times. The ability of a species to keep adapting to a changing environment has limits, which will vary with the species. For example a study of the Australian tropical rainforest fly (*Drosophila bircha*) showed that there is variation across the population to resist desiccation. After intense selection for 30 generations, the fly lacked the ability to evolve further resistance[56]. The population is now at the edge of its ability for genetic evolution to change, in this case, to the potential climate change of increased dryness.

For island species, flexibility or plasticity is an advantage when the environment changes. The change could be either by the island changing or the species colonising a new island. For birds, foraging flexibility is the primary variable affecting success of colonisation[21]. Plasticity for phenotype may assist genetic evolutionary change to a better-adapted species for the new environment[96,39]. For example, a change in behaviour by an animal may favour selection for another feature of the animal, such as beak size. However, climate change impacts that decrease the population size of isolated flora and fauna species may result in decreased genetic diversity within the population. This may make them less able to adapt to the stresses of climate change[123].

### Migration of flora and fauna to more suitable conditions

Many islands have a limited climate range or diversity of habitat and there is little capacity to move or migrate to another habitat on an island. There are few options for flora to migrate between islands especially if they do not have long distance dispersal mechanisms. Many of the plants and animals, including freshwater species, that were marooned on continental islands when sea level rose since the last ice age cannot disperse long distances over water and will die out as the climate changes. As islands change and some species disappear new opportunities for pioneering species may arise. The capacity for propagules to reach new island sites is always a constraint on islands. Colonisation capacity depends on the location of suitable source material of seeds and other propagules, distance from land, ocean and tidal currents and weather patterns. The number of species at risk on continental islands is greater than the number of available long distance colonisers and so the biodiversity of flora and fauna on continental islands will decrease. As sea level rises above one metre and cays and low islands disappear, the distances between the remaining islands and to the mainland will increase, making colonisation even more difficult.

Fauna will move depending on their sensitivity to climate change, their mobility, life span and availability of key needs[102]. Any emigrating fauna might face the challenges of finding enough food, avoiding new predators, finding new breeding sites, and new courtship requirements[125]. Even if new habitat was available, the ability for many fauna to migrate across water is limited.

## 20.4 Summary and recommendations

### 20.4.1 Summary of key vulnerabilities

Key flora and fauna at most risk from climate change are discussed below.

### Vulnerability of continental island vegetation

Increases in air temperature causing greater evaporation, if combined with a decrease in average rainfall and increased periods of drought, and a higher fire risk, will result in a general shift in vegetation from rainforest and wetland vegetation to more sclerophyll shrubs and trees. Water stress will be moderated through the increasing concentration of atmospheric $CO_2$ improving the efficiency of photosynthesis. However, this is only likely on islands with adequate nutrients such as bird breeding islands, or with nitrogen fixing plants, and where temperature is not hindering metabolic processes. Weeds, pests and diseases are likely to have greater impacts on stressed and changing vegetation. Continental vegetation is likely to be less diverse and be more sclerophyllous. The most important factor affecting the uncertain future of rainforest patches on GBR islands is the amount of rainfall.

### Vulnerability of island flora biodiversity

The impact of multiple factors may favour some flora and fauna species and disadvantage others. Conditions on islands may become suitable for new species as they become unsuitable for others. Some remnant flora species on continental islands are unlikely to have as much plasticity as pioneering cay foreshore plants and may not adapt to the changing environment. Remnant vegetation on Hinchinbrook Island peaks will disappear. Colonisation of new species onto islands is slow, slower than the expected rates of species loss from islands. Biodiversity of the island is likely to decrease as losses of species outweigh recruitment of new species.

### Vulnerability of rainforests and montane heathlands

Rainforests and montane heathlands will be reduced by warmer, drier conditions, particularly if the average rainfall decreases, or rain events become more infrequent. Increased fire risk, greater cyclone damage, decreases in nutrients brought by pigeons and other frugivores, less pollinators and seed dispersers and increased pest risk will affect rainforest habitats. Rainforests are likely to decrease in area on GBR Islands. Conversely, if rainfall increases, some lowland mesophyll rainforest may expand. Shaded understorey plants may increase their photosynthesis and biomass with higher atmospheric $CO_2$.

### Vulnerability of grasslands

Grasses are favoured by drier conditions and increased fire risk over herbaceous species. However, an increase in photosynthetic efficiency by $C_3$ shrubs with higher $CO_2$ concentrations in the air may cause them to out compete and expand into some of the $C_4$ grasslands. Other climate-induced effects on grassland include increased weed and insect pest risks. The future for island grasslands is uncertain with increases or decreases possible and fire management remaining a critical issue.

### Vulnerability of foreshore vegetation

Most foreshore flora species are pioneers and show plasticity to adapt to changing conditions. They will adapt as sea level rises and storms alter shorelines. Beach and seashore vegetation on continental islands will be relocated further inland. The rise in salinity of soil in the newly formed coastlines will promote salt tolerant seashore plants at the expense of current established plant species. Dynamic shorelines are vulnerable to weed infestation that may out-compete native vegetation.

### Vulnerability of cay vegetation

On large cays, larger trees depend on the freshwater lenses. Decreases in rainfall or increased evaporation rates will affect the freshwater lenses, which will affect the growth of trees.

Pisonia forests are tolerant of temporary saltwater and freshwater inundations. Cay vegetation will be more vulnerable to pest impacts as temperature increases improve the metabolic rate of pests. If seabirds decline the subsequent nutrient loss will disadvantage pisonia trees. Reduced turtle nesting will make the shoreline less dynamic. Cay vegetation is likely to adapt to changes with an altered species composition, until cays are lost completely in the long term high sea level rises.

### Vulnerability of freshwater wetlands

Most wetlands on continental islands will be greatly affected by a combination of higher evaporation due to increases in temperature, inundation from a rise in sea level, decreases in rainfall (if this happens), an increase in the number or length of droughts and increased fire risk. If average rainfall increases and there are not also prolonged dry periods, wetlands will be enhanced. Overall a net loss of wetlands is predicted in the short term and a severe loss in the long term when lowland areas of continental islands are inundated. The only wetlands that will persist will be the mostly ephemeral streams on slopes and perched swamps on hills on a few islands.

### Vulnerability of island fauna

Terrestrial fauna species are highly dependent on the condition of their habitat and as vegetation alters the fauna must adapt, move or perish. Foliage feeders such as possums, koalas, rock wallabies and insects will be disadvantaged by the decrease in the food quality of leaves due to increased $CO_2$ in the

air altering the carbon and nitrogen balance in the leaves. An increase in sclerophyllous vegetation, due to increased water stress from higher temperature and lower rainfall, will disadvantage some plant eaters and advantage others. If rainfall decreases or becomes less frequent, drier conditions will lower the productivity of the leaf litter. Fauna that depend on invertebrates on the ground or in trees will find less food. A decrease in plant food quality and availability will affect eaters of nectar, pollen, fruit, and seed. The impact will continue up the food chain to insectivores and carnivores. Fauna can migrate, adapt or die-out. With many island fauna species unable to migrate between islands, adaptation is the only option for survival. Many animals are likely to decrease in abundance. A relative few fauna species will be advantaged by changes to island habitats.

### Vulnerability of island fauna biodiversity

Impacts on terrestrial fauna depend on the faunal species ability to migrate to suitable habitat elsewhere, their ability to move to find new habitat or are tied to their plasticity to survive or adapt to an altered environment. Wetland and rainforest species are particularly vulnerable as their limited island habitats at risk. Endemic and rare species at risk include: the Capricorn white-eye which favours pisonia forests, the Bramble cay melomys as it only lives on one small island[73], the Proserpine rock-wallaby as it favours a limited vegetation type including beach scrub on Gloucester Island[87], the Whitsundays azure butterfly as it depends on food plants on Whitsunday Islands[113], and the Dawson yellow chat as it is confined to coastal saline plains[44]. All these species are likely to decline or disappear. Fauna on islands are likely to show a decline in species biodiversity similar to flora.

### Vulnerability of seabird and shorebird nesting

Increases in sea surface temperature, changes in ocean currents and ENSO events can decrease food availability for seabirds and lower their breeding success (Congdon et al. chapter 14). For many seabirds the impact of decreased food availability will be far more significant than short-term changes to nesting habitat[8,33].

In the short term, as sea level rises new cays may be created and small ones increase in size. Increased wave action and greater cyclone strength will probably make cays, sandy beaches and spits more dynamic. Beaches may be new or altered but they will provide seabirds with places to nest. Many seabirds return to nest on familiar beaches but if those sites no longer exist, seabirds have some capacity to find alternative sites, including on other islands if they are available. Potential new seabird breeding sites must have sufficient food within foraging range to support breeding and not be already occupied. Ground nesting shorebirds and seabirds that nest on bare ground close to the intertidal mark such as the black-naped tern (*Sterna sumatrana*) and little tern are adapted to nesting in dynamic landscapes and frequently select new sites each year[97].

Some seabird species, such as the brown booby (*Sula leucogaster*), show strong nesting site fidelity[90]. If nesting becomes unsuitable on one island they will move to nearby islands for nesting but the potential for moving to distant islands if an island group such as the Swains Cays disappears is much less certain.

In the longer term most cays and low sandy islands are expected to disappear, reducing nesting options for seabirds and forcing them to the higher ground of continental islands and the predator-inhabited mainland. Some seabird species, such as the bridled tern (*Sterna Anaethetus*), will be able to nest among rocks and vegetation on continental islands. Birds preferring open ground may struggle to find sites. Eventually there will be a loss of breeding islands close enough to feeding grounds with sufficient food to raise chicks. The population of breeding seabirds on the GBR is likely to decrease when the Swains Cays, Capricorn Bunker Group and Far Northern Cays disappear.

Several species of seabird will be impacted if woody island vegetation is altered; including black noddies that nest on tree branches, red-footed boobies that nest on shrubs and wedge-tailed shearwaters that use the pisonia forest roots to support nesting burrows. Even changes to island fauna can affect coastal birds. Rufous night herons (*Nycticorax caledonicus*), that time their nesting on Raine Island to feed on turtle hatchlings[8], will be affected if climate change affects turtle breeding success.

### Vulnerability of migratory birds

Migratory animals are particularly vulnerable to climate change as they rely on multiple habitats and time their arrival and departure from locations to coincide with food availability and suitable weather. Assessments of migratory birds in Europe and North America predict serious declines as a result of even small changes in temperature[125]. Changes have been observed in Australian birds including species expanding their ranges southward and altering timings of migration patterns[23].

Migratory birds that time their migration to coincide breeding with the time when most food is available are more at risk than resident birds. Migrations may get out of synchronisation with peak food availability[22]. A reduction and/or loss of low islands, such as inshore sand islands and coral cays and their surrounding intertidal mud or sand flats could reduce the survival of migratory shorebird species. Many shorebirds of the GBR breed in the Arctic regions of northern Asia during the northern summer and migrate to feed on the intertidal mudflats of the GBR for the southern summer, or pass through as migrants. The eastern curlew, red knot (*Calidris canutus*), and bar-tailed godwit (*Limosa lapponica*) are good examples[54].

These shorebirds must get sufficient food from the intertidal mudflats to put on as much as a third of their body weight as fat to fuel migration flights[71]. The tight energy budgets of shorebirds will be compromised if GBR intertidal flats are inundated and the birds will be similarly impacted at re-fuelling stops on intertidal wetlands in Asia on their migration route. Their nesting sites are also vulnerable. Many northern hemisphere shorebird breeding grounds are moving north as temperatures warm and vegetation changes, increasing migration distances to the GBR. For some species such as the red knot that breed in the Arctic, habitat is running out and there is nowhere further north to go[100].

The requirement for functioning ecosystems en-route and at each end of the migration also applies to some populations of seabirds which migrate to the GBR from nesting sites in the northern hemisphere, for example, the population of roseate terns that breeds in North Asia and winters on the Swain Cays[91]. Populations of northern hemisphere breeding shorebirds and possibly seabirds are likely to decline in the GBR.

### Vulnerability of migratory land birds

Most land birds of the GBR do not migrate but several species, such as pied imperial pigeons, spangled drongos (*Dicrurus bracteatus*) and several cuckoos, migrate to northern islands such as Papua New Guinea. These are not the long migrations of land birds from temperate to tropical areas typical of many terrestrial European and North American nesting song birds, where timing is essential

for breeding success[125,16]. Land birds migrating to southeastern Australia from islands to the north of Australia have arrived on average 3.1 days per decade earlier, and departed 8.1 days per decade later, since 1960[14]. Timing shifts for the GBR land birds are unlikely to be as pronounced, as most species are confined to the tropics where temperature changes between seasons are not as critical for bird life cycles[26]. GBR migratory birds still depend on having functioning ecosystems at both summer and winter habitats and on islands on the migration routes. Pied imperial pigeons have the capacity to roost and nest in a variety of vegetation and are likely to adapt to changes in island vegetation in the short term. A loss of low wooded islands may limit their roosting options in the long term.

#### Vulnerability of turtle nesting

In the short-term beaches of cays and continental islands will become more dynamic, but they will still be available for turtle nesting. The long-term loss of cays and many beaches of islands will reduce turtle nesting options.

### 20.4.2 Summary of impacts

This chapter cannot provide a quick or definitive answer to the question of *'What is the future of the GBR's terrestrial island environments during current and predicted climate change?'* The impacts of climate change are inevitable. According to Melillo et al.[80] biogeography models, climate change has the potential to affect the structure, function and distribution of all terrestrial ecosystems. The timing and strength of these impacts on the diverse GBR islands depends on many variables including current factors such as soil type, nutrient availability, salinity tolerance, food webs, migration and dispersal potential as well as all the expected changes in climate including rainfall, storm strength, temperature, $CO_2$ concentration, weed and pest risk and interactions with other plants and animals.

For GBR islands, the point when cays cease to build and begin to erode is a critical moment. We have used this moment to differentiate short-term and long-term impacts.

In the short term, during the next several decades, the greatest impacts are likely to be due to variations in rainfall and rising air temperature causing water stress to plants and animals, and an increased risk from fire, weeds and disease. The effects of elevated $CO_2$ at plant community levels are uncertain. Habitats may become structurally similar to those we see today, but with shifts of competitive balance among existing island species resulting in very different species in the communities.

Many islands with reduced land area, increased isolation and heightened competition among wildlife will most likely have a reduced plant and animal biodiversity. Tropical habitats and communities as well as tropical weeds and diseases will extend further south and the ranges of more temperate species will shrink. Increased cyclone strength and rising sea level will make cays, sandy beaches and spits more dynamic but most seabirds and turtles will still have places to nest if they are flexible and able to adapt.

In the long term, as sea level rises more than one metre above present levels, most cays and lowlands of continental islands will erode or be inundated. Some vegetation types, such as pisonia closed-forest and wetlands, will be reduced to refuge sites. Some plant and animal species will become locally extinct.

If there is a major sudden rise in sea level of several metres from a Greenland or Antarctic Ice Sheet melting, the impacts will be immediate and catastrophic for habitats on cays and lowlands of continental islands.

Eventually climate changes will stabilise and a new dynamic of flora and fauna will become established. However, as community reconstruction often takes millennia, there will be continuous changes for centuries at least[123].

A summary of impacts in the short and long term is presented in Table 20.4.

***Table 20.4*** *Summary of the effects of climate change on key natural values of GBR islands*

***Short-term impact*** *– Less than one metre sea level rise, air temperature increases 2 to 3°C, sea water temperature increases 1 to 2°C, small rainfall and cyclone changes, and moderate $CO_2$ increases*

***Long-term impact*** *– Greater than one metre sea level rise, air temperature increases greater than 3°C, sea water temperature increases greater than 2°C, moderate rainfall and cyclone changes, high $CO_2$ increases*

| GBR Island Value | Short-term impact | Long-term impact |
|---|---|---|
| **Flora** | | |
| Coral cay vegetation | Altered species composition | Coral cays disappear, some species survive on continental islands |
| Pisonia forests | Maintained | Survive as refuge patches on continental islands associated with seabird nesting. |
| Continental island sclerophyll forests and scrubs | Increased in area, altered species composition, higher fire risk | Fewer species, high fire and disease risk |
| Rainforests | Uncertain. Possible reduction in area and species but may expand if rainfall increases | Uncertain. Possibly contract to small remnants |
| Montane heathlands | Reduced in area and species | Local extinction is highly probable |
| Freshwater wetland vegetation | Reduced in area and species | Survive only in water holes and streams on slopes |
| Dune and shore vegetation | Relocation and alteration to species composition | Major relocation and reduction in area |
| Continental island grasslands | Impacted by expanding $C_3$ shrubs but depends on fire regimes and drought. May increase or decrease | Uncertain future. Dependent on fire management |
| Rare continental island flora | Uncertain future | Mostly extinct on islands |
| Weeds | Increase in area affected by the elevated disturbance | Increased area affected on continental islands |
| Invertebrate pests | Possibly increase | Possibly increase |

| GBR Island Value | Short-term impact | Long-term impact |
|---|---|---|
| **Fauna** | | |
| Endemic coral cay fauna | Probably survive | Uncertain, likely to be extinct |
| Endemic and rare continental island fauna | Possibly survive | Uncertain, some future, possibly extinct on islands |
| Seabird and turtle nesting sites | Adapted to new nesting sites on cays, continental islands and mainland | Reduced to a few new sites on continental islands and the mainland |
| Freshwater wetland fauna including fish and frogs | Reduced number of species | Uncertain future, reduced to stream species only |
| Pied imperial pigeons | Survive as opportunistic migratory birds in island rain forests and mangroves | Reduced to refuge sites in residual rainforest and mangroves on continental islands |
| Fauna of sclerophyll forest, scrub and grasslands | Uncertain, some species may increase and others decrease | Possibly survive. Foliage herbivores likely to be reduced, higher disease risk |
| Fauna of rainforests and montane heaths | Reduced abundance and species richness, except if rainfall increases | Some species may survive in small refuge sites as rare island species |
| Migratory shorebird feeding and roosting sites | Probably viable but altered composition and size of flocks | Uncertain future, may adapt to refuge sites in lower numbers |
| Resident shorebird nesting, feeding and roosting sites | Relocated along new shores and viable | Reduced to new sites on continental islands and/or mainland shores |

### 20.4.3 Management actions

The most important management action is to lessen the impact of climate change by encouraging global reductions in $CO_2$ and other greenhouse gases[109]. However given current trends, many impacts of climate change are inevitable, already occurring or will be impossible to prevent on islands of the GBR. Policy decisions should be made, particularly:

- What time scale to manage for: 20 years, 100 years or 200 years?
- What values and attributes of GBR islands are most important to protect and support by building their resilience, and what values can we accept to lose?

Potential management actions for GBR islands include:

- Implement biological inventories to identify high value sites on islands and predict the impacts of climate change, particularly changes to island vegetation and geomorphology.

- Minimise other human related impacts on islands and maximise natural resilience of habitats to climate change.
- Ensure management and site plans, and environmental impact assessment, for islands and their surrounds consider climate change.
- Educate managers, the public and interest groups about the impacts of climate change on islands and other components of the GBR ecosystem.
- Implement actions to ensure the survival of the Bramble Cay melomys and other endemic fauna and flora including establishing populations at alternative sites.
- Plan fire management to consider the increased fire risk and growth of fire adapted woody plants on islands and increase fire management actions accordingly.
- Increase weed and pest monitoring, control and eradication actions to take account of an increased risk of weed establishment and spread. Focus on $C_3$ weeds.
- Use pest and disease monitoring data to prepare response actions for pest and disease outbreaks on GBR islands.
- Monitor coastal bird breeding effort and turtle hatchling success to determine if any declines are related to changing nesting habitat.
- Define nesting requirements for coastal birds and turtles on GBR islands, and actively manage bare substrates and island vegetation at key existing and potential future coastal bird nesting sites.
- Monitor roosting and feeding sites for shorebirds and undertake works that ensure safe roosting sites are maintained or provided.
- Determine the risk and feasibility of management actions to reduce impacts on key wetland sites including water management works and barriers to saltwater incursion.
- Monitor changes to significant vegetation communities eg montane heath on Hinchinbrook Island, grasslands at the Whitsundays Group and pisonia forests on the Capricorn Bunker Group.
- Conduct site assessments of the potential impacts of sea level rise and intense storms for key visitor sites.
- Determine the feasibility of reducing impacts on key visitor sites and facilities, including engineering work or barriers, or relocating sites.
- Design any future visitor facilities to take account of sea level rise and changes to island geomorphology and vegetation.

### 20.4.4 Research actions

Research should identify specific risks to important natural values and how the risks can be minimised and the values made more resilient. Specifically:

- Identify and systematically observe relevant variables that provide an increased understanding of changes in vegetation caused by both non-climate change factors and climate change factors.
- Monitor and diagnose vegetation as it evolves during climate change, being cognizant of the complex interactions between climate, the islands and the vegetation.
- Investigate potential impacts of climate change on key vegetation communities including pisonia forest and grasslands, rainforest, banksia/casuarina montane heathlands and wetlands.
- Investigate if habitat of key fauna (eg Proserpine rock-wallaby, Capricorn white-eye, Dawson yellow chat, Bramble Cay melomys and Whitsundays azure butterfly) will continue to exist on their current islands, and investigate if other islands are, or may become, suitable habitat.
- Investigate the geomorphology of key coral cays and whether they are likely to increase or decrease in size as sea level gradually rises, especially Raine Island and other far northern outer reef cays, the Capricorn Bunker Group and the Swains Reefs.
- Identify and determine control strategies for weeds most likely to adversely impact islands under current and predicted climate change.
- Investigate if impacts of pests and diseases of island species and habitats are linked to climate change, (eg scale insect infestation on pisonia vegetation in the Capricorn Bunker Group).
- Identify current and potential seabird feeding areas and potential nesting sites within feeding range suitable for active enhancement as nesting sites.
- Investigate techniques for actively managing turtles and seabirds nesting on beaches and islands.
- Investigate techniques to actively manage island wetlands and coral cays including revegetation and reintroduction of key species, engineering works and water management.

Climate change impacts on GBR islands are large, inevitable and challenging. The only certain thing is that we live in interesting times.

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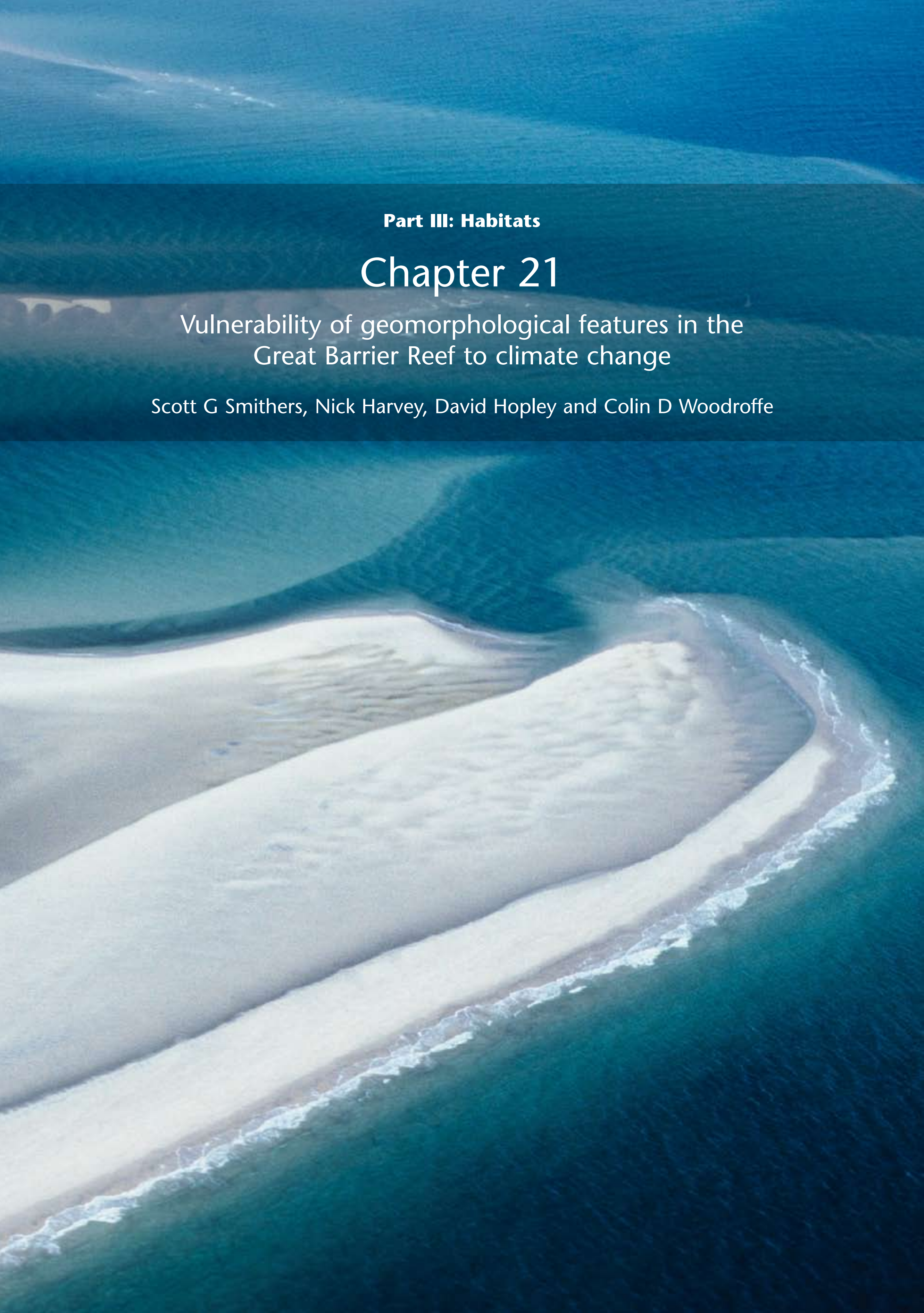


**Part III: Habitats**

# Chapter 21

## Vulnerability of geomorphological features in the Great Barrier Reef to climate change

Scott G Smithers, Nick Harvey, David Hopley and Colin D Woodroffe

## 21.1 Introduction

The Great Barrier Reef (GBR) is the largest contiguous coral reef ecosystem in the world[81,49]. That it is possibly the largest geomorphological structure ever created by living organisms is less widely appreciated. The GBR extends through approximately 15 degrees of latitude and more than 2100 km along the northeast Queensland coast, covering an area of 344,500 km$^2$[82]. It includes more than 2900 reefs of varying types (eg fringing, patch, cresentic, lagoonal, planar), dimensions and stage of growth, which together occupy greater than 20,000 km$^2$, or about 5.8 percent of the total area of the GBR[81,82]. Three hundred or so coral cays, and more than 600 continental or high islands occur within the GBR. The mainland coast, which can be broadly separated into sandy shorelines and mangrove-lined muddy coasts and estuaries (rocky coasts are far less common)[80], is another important and dynamic geomorphological component of the GBR.

The geomorphology and ecology of the GBR are strongly interdependent – the reefs are almost entirely the skeletal remains of a myriad of calcium carbonate secreting fauna and flora. A suite of organisms and ecological processes are involved in the production, consolidation, modification and redistribution of these products to form many of the GBR's geomorphological features. Conversely, geomorphological features are important to reef ecology. They physically structure habitats for various biota and influence the distribution of physical processes (such as waves and currents) important to many reef organisms. At a larger scale, outer reefs separate the inner lagoon and open ocean, and control cross-shelf hydrodynamic energy gradients important for many species. Biogeographic and other influences are important[156], but the extraordinary habitat complexity and biological diversity found on the GBR can be largely attributed to the geographical opportunities of latitudinal and cross-shelf gradients provided by its impressive scale.

This chapter provides an overview of the vulnerability to climate change of five of the GBR's major geomorphological features: i) coral reefs, ii) reef islands, iii) high island beaches and spits, iv) mainland sandy coasts, and v) mainland muddy coasts. The vulnerability of biota associated with these features is assessed in other chapters (Lovelock and Ellison chapter 9, Hoegh-Guldberg et al. chapter 10, Congdon et al. chapter 14, Fabricius et al. chapter 17, Sheaves et al. chapter 19 and Turner and Batianoff chapter 20). Vulnerability is defined as the degree to which a system or species is susceptible to, or unable to cope with, the adverse effects of climate change[1].

Vulnerability assessments for geomorphological features are complicated because exposure to different climate change stressors varies geographically, and sensitivity can differ according to the rate and nature of predicted changes relative to contemporary and past patterns of exposure (Table 21.1). For example, a reef island's sensitivity to sea level rise would vary according to tidal range, late Holocene relative sea level history, and exposure to other sea level fluctuations such as those associated with El Niño–La Niña cycles. Complex feedbacks throughout the system present additional challenges, as do the differing timescales at which many ecological and geomorphological processes operate, and the variable significance of changes at different spatial scales. Our evaluations of the potential impacts, adaptive capacity and the vulnerability of geomorphological features are thus by necessity rather generalised, speculative, and have varying application across the GBR.

***Table 21.1*** *Possible conditions affecting the exposure and sensitivity of different geomorphological features of the GBR to climate change factors*

| **Climate change factor** | **Exposure and sensitivity affected by:** |
|---|---|
| Rising sea level | *Late Holocene relative sea level history:*<br>Has late Holocene relative sea level fall and emergence provided a buffer?<br>*Rate of relative sea level change:*<br>Is rate of rise faster than vertical accretion rate or can the feature keep up with sea level rise?<br>What are the consequences of increased depth (eg increased wave penetration, remobilisation of surficial sediments)?<br>*Tide range:*<br>How do projected rates of rise compare with tidal fluctuations? Are changes of mm per year significant where tidal ranges can be more than 7 metres?<br>*Total depth range:*<br>What depth range can the feature survive in, and how precisely are these limits constrained? |
| Rising sea surface temperatures | *Late Holocene relative sea level history:*<br>Has late Holocene relative sea level fall and emergence already exposed shallows to higher temperatures via ponding, etc?<br>*Exposure to ameliorating phenomena such as mixing, upwelling etc:*<br>Mixing by currents, turbulence or upwelling with cooler waters will reduce potential for thermostratification and excessive heat build-up<br>*Existing thermal regime:*<br>What is the magnitude of critical temperature change compared to the existing thermal regime, and how will changes influence critical sediment production, stabilisation or transport processes?<br>*Tide range:*<br>Areas of higher tide range and tidal currents will generally be better mixed and less vulnerable to excessive temperatures |
| Increased tropical cyclone activity and surge | *Late Holocene relative sea level history:*<br>Is the feature emergent and lithified?<br>*Tide range:*<br>How does projected surge compare with tidal range?<br>*Existing exposure to cyclone impacts:*<br>Is the geomorphological feature already adjusted to high-energy conditions?<br>*Position across shelf:*<br>Outer shelf reefs are generally more exposed to higher wave energy than inner reefs, but variations in this pattern do occur<br>*Coastal configuration, shelf gradient and depth:*<br>Are coastal configuration and shelf bathymetry likely to enhance storm surge potential? |

| Climate change factor | Exposure and sensitivity affected by: |
|---|---|
| Enhanced or reduced rainfall | *Proximity to the coast:*<br>Inshore areas are more exposed to flood impacts and changed sediment/ contaminant delivery to the GBR lagoon<br>*Degree of enclosure:*<br>Enclosed settings with poor mixing more exposed to lowered salinities<br>*Nature of rainfall pattern change:*<br>How do projected changes compare with existing rainfall patterns?<br>*Degree of oceanic mixing:*<br>Influence ameliorated where waters well mixed |
| Ocean acidification | *Temperature and aragonite saturation state:*<br>Acidification is likely to vary within the GBR as a function of temperature and alkalinity (see chapter 17) |

An appreciation of the nature and rates of past environmental changes on the GBR provides an important starting point for assessments of how it might respond to climate change and of the significance of any adjustments. The geological record documents numerous cycles of sea level change of greater magnitude and pace than those predicted for the future, through which corals have survived and the GBR has repeatedly re-established[158]. Of course, optimistic assessments of coral reef resilience to predicted environmental changes based on past survival must be tempered by acknowledgement of the extra pressures most now endure[85,124,45]. These issues are central to a longstanding debate about whether reefs are robust (a geological perspective) or fragile (an ecological position). Reviews of this debate generally conclude that both positions are valid, with each having merit at appropriate temporal and spatial scales (eg Done[38], Grigg[57]). Geomorphology is uniquely positioned to offer an integrative perspective of reef condition that is at a scale appropriate for many climate change assessments.

## 21.2 Geomorphological features discussed in this chapter

### 21.2.1 Coral reefs

Numerous definitions of a coral reef exist, with varying emphasis on ecological and geomorphological attributes[132,92]. Coral reefs are commonly defined geomorphologically as biologically influenced, wave-resistant structures composed of coral framework and carbonate sediments[70]. Most coral reefs are dominated by calcium carbonate produced by corals, although coralline algae, molluscs, foraminiferans and various other organisms can be significant contributors. For a 'true' coral reef to develop the skeletal remains of these organisms must accumulate to form a deposit stable enough to resist dispersion by waves and currents. Biological influence on coral reef geomorphology is not limited to skeletal carbonate production – reef organisms also erode, transport, bind and consolidate reef materials[51,84]. The above definition emphasises coral framework as an important structural element, but detrital facies are recognised as volumetrically more important on many reefs[110,82]. The production and transport of detrital materials during storms is an important constructive geomorphological process for many reefs[109,136], including those on the GBR[30,142,82].

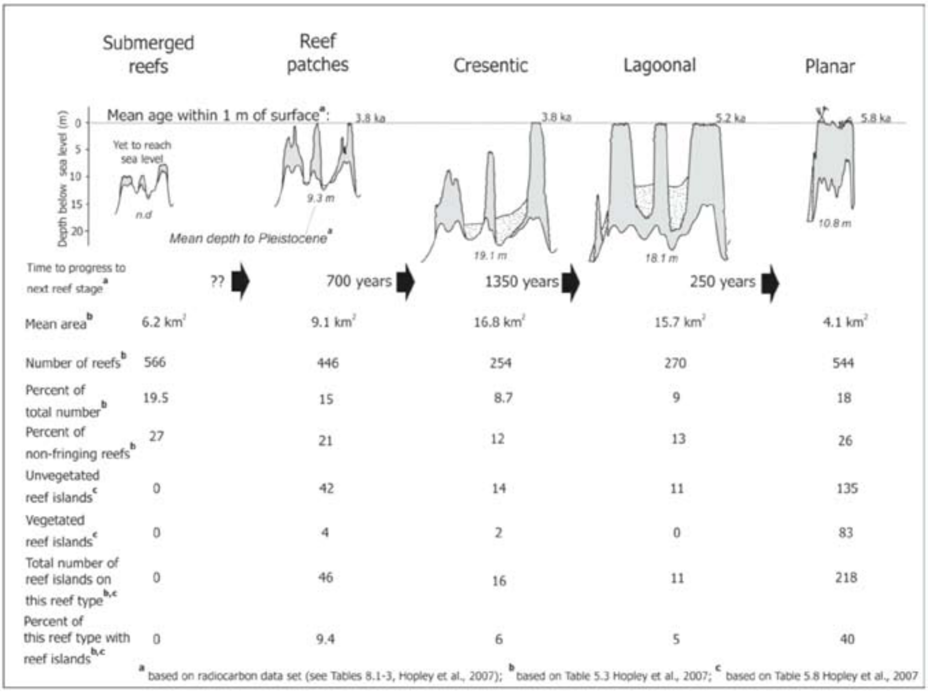
The modern GBR began to grow after the last ice age when rising seas flooded the continental shelf. For many years it was believed that modern reef growth on the GBR started within a 'narrow take-off envelope' between 8300 and 7500 years ago[31], but re-interpretation of detrital sediments at the base of reef cores suggests a much broader initiation interval beginning as early as 9900 years ago[82]. Outer- and mid-shelf reefs typically established on the limestone remnants of reefs formed during previous sea level highstands, the last of which occurred around 125,000 years ago[94]. Significantly, conditions amenable for reef growth have existed on the central GBR shelf for about 15 million years[32], but reef cores suggest that coral growth began on the northern GBR only 600,000 years ago, and growth equivalent to modern reef growth did not begin until 450,000 to 360,000 years ago[158]. As reviewed by Pandolfi and Greenstein (chapter 22), conditions suitable for reef growth have been the exception rather than the rule for much of the GBR's history. For most of the time, reef growth was restricted to the deeper shelf edge by low glacial sea levels[70,82]. Just five or six highstands (each lasting less than 10,000 years) during which reef growth comparable to present could flourish have occurred during the GBR's history[158]. Fluctuating sea level and associated environmental changes (often rapid and abrupt) have dominated the GBR's past (see chapter 22).

Comprehensive accounts of the tremendous geomorphological diversity observed across and between individual reefs within the GBR are available in Hopley[70] and Hopley et al.[82]. This variety largely reflects the ecological and geomorphological zonation of environmental parameters across reefs, and across the shelf and latitudinally[74,36,37]. Reef zonation is dynamic, changing as reefs grow or conditions change. The concept of reef geomorphology progressing through an evolutionary sequence was introduced by Darwin[29] for mid-ocean reefs, and was offered as a reason for the 'gradational nature' of GBR shelf reefs by Maxwell[114]. Hopley[70,72] extended Maxwell's work and developed a morphogenetic classification that explains differences in reef morphology as a function reef evolutionary stage. At the simplest level three broad classes were identified, each largely determined by the depth and size of a reef's foundations, and its relative sea level history:

- Juvenile reefs: reefs not yet at sea level, perhaps because they have risen from deep foundations or started growing late.
- Mature reefs: reefs with established reef flats but retaining a lagoon, possibly because reef foundations were larger or deeper than for senile reefs.
- Senile reefs: reefs with infilled lagoons and planar reef tops, usually formed over small and shallow foundations subject to late-Holocene sea level fall (Figure 21.1).

Under stable sea level conditions reefs will develop through this sequence to a natural point of senescence. Approximately 2080 of the GBR's 2900 named reefs are easily classified with this morphogenetic scheme (ribbon and fringing reefs cannot), with around half at the juvenile stage (submerged and patches), and 25 percent at both the mature (crescentic and lagoonal) and senile (planar) stages. The spread of reef types at various stages in the evolutionary sequence is therefore suitable for the continued maintenance and development of habitat diversity and function. However, broad regional patterns in foundation depth, relative sea level history, and thus reef stage and morphology occur[70,81,82]. Therefore some reef types are spatially concentrated and are vulnerable to critical changes in these geographic areas (see section 21.3.1.1).

*Figure 21.1* Shelf reef classification and summary statistics (after Hopley et al.[82])



| | Submerged reefs | Reef patches | Cresentic | Lagoonal | Planar |
|---|---|---|---|---|---|
| Time to progress to next reef stage[a] | ?? | 700 years | 1350 years | 250 years | |
| Mean area[b] | 6.2 km² | 9.1 km² | 16.8 km² | 15.7 km² | 4.1 km² |
| Number of reefs[b] | 566 | 446 | 254 | 270 | 544 |
| Percent of total number[b] | 19.5 | 15 | 8.7 | 9 | 18 |
| Percent of non-fringing reefs[b] | 27 | 21 | 12 | 13 | 26 |
| Unvegetated reef islands[c] | 0 | 42 | 14 | 11 | 135 |
| Vegetated reef islands[c] | 0 | 4 | 2 | 0 | 83 |
| Total number of reef islands on this reef type[b,c] | 0 | 46 | 16 | 11 | 218 |
| Percent of this reef type with reef islands[b,c] | 0 | 9.4 | 6 | 5 | 40 |

[a] based on radiocarbon data set (see Tables 8.1-3, Hopley et al., 2007); [b] based on Table 5.3 Hopley et al., 2007; [c] based on Table 5.8 Hopley et al., 2007

Radiocarbon ages from reef cores and reef flat microatolls indicate that reefs can rapidly move through the evolutionary sequence. For example, many inner northern GBR reefs progressed from submerged reef patches to planar reef tops in a few thousand years[153,137]. Simple models using present-day carbonate production rates suggest very small lagoonal reefs may become planar reefs in under 500 years, and larger reefs of 20 km diameter (greater than 300 km² area) with 10 metre deep lagoons can reach senility in less than 6000 years[82]. Significant environmental and ecological change would accompany this intrinsic geomorphological development. Well-flushed submerged 'catch-up' reefs[116] with luxuriant growth over the platform would become increasingly enclosed and dominated by detrital sediments. The outer reefs had their most vigorous period of growth between approximately 8500 and 5500 years ago, since then their structural and ecological diversity has progressively declined[82]. As noted above, about 25 percent of GBR shelf reefs are near the end of this sequence.

Fringing reefs cannot be easily classified using Hopley's[70] evolutionary scheme, and due to their proximity to land are widely perceived as especially vulnerable to changes in terrestrial conditions. Clearly, however, many fringing reefs on the GBR have long been exposed to a range of terrestrial influences, and their sensitivity to these may actually be relatively low. Smithers et al.[143] noted that the many fringing reefs in the GBR underwent a period of active growth between about 7500 and 5500 years ago, but later 'turned off' as accommodation space was exhausted. The histories of these reefs are relevant to assessments of future vulnerability in several ways. First, they 'turned off' due to intrinsic

factors, although climate fluctuations were argued to modulate reef growth rates. Second, several of these senile reefs have not significantly changed size for thousands of years despite supporting healthy coral communities in historical times. These results demonstrate the long-term resilience of coral reef structures through prolonged periods of diminished carbonate production, and the pitfalls of assuming simple relationships between coral community condition and reef growth and maintenance.

### 21.2.2 Reef islands

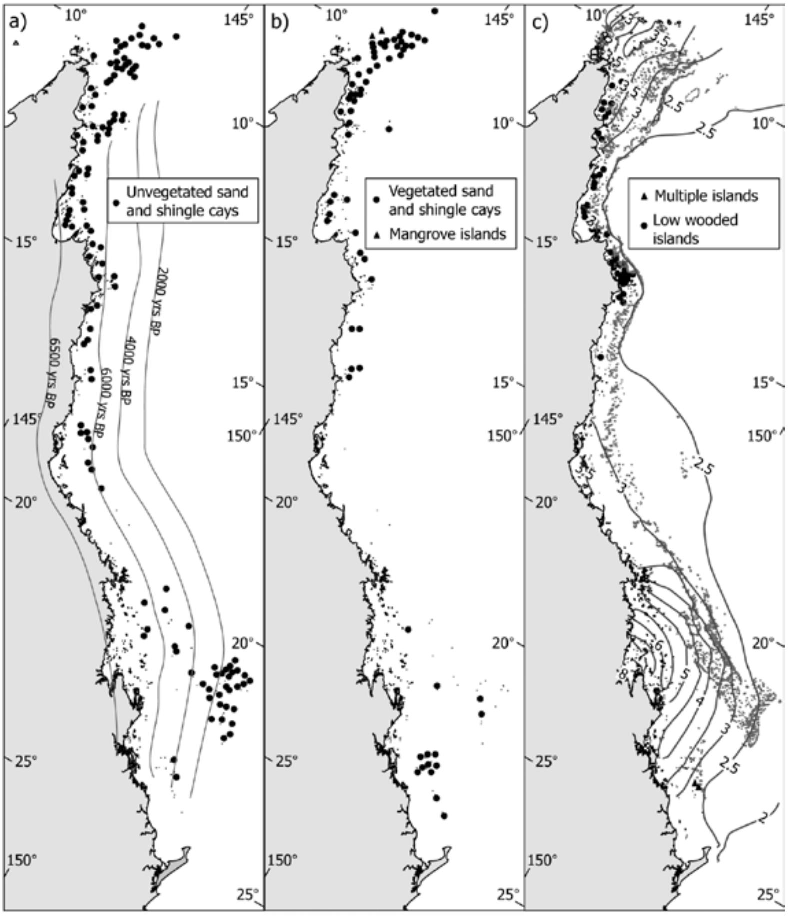
Reef islands (cays) are low-lying accumulations of reef-derived sediments, portions of which may be lithified, deposited on reef platforms at or close to sea level. They form where waves refract around and over reefs and converge at a focal point on the reef platform where sediments are deposited[54,79]. Cays are generally absent from larger reefs or those with a geometry that impedes centripetal wave refraction. The long-term development of reef islands in areas of dense reef network is similarly constrained, as low ambient wave energy cannot effectively concentrate sediment deposition[54]. Sand cays formed under ambient wave and climate conditions typically accumulate near the leeward edge of the reef platform, whereas those composed of coarser sediments moved during storms usually form closer to the windward reef edge. Gourlay[54] presents an excellent summary of reef island formation processes.

The geomorphology of reef islands on the GBR is varied, reflecting the range of latitude and climate, the variable geometries and relative sea level histories of the reefs on which they form, and the diversity of sediments of which they are composed[79,82]. Detailed descriptions of the reef islands found on the GBR are presented in Hopley[70,79] and Hopley et al.[82]. Unvegetated sand or shingle cays are the simplest reef islands geomorphologically, and usually the youngest and most dynamic. The complex low wooded islands composed of a windward shingle island, a leeward sand cay, and varying degrees of mangrove development over the intervening reef platform, are typically the most complex and stable. Surprisingly few reef islands on the GBR have been subject to detailed geomorphological investigations.

Most (72.7%) reef islands on the GBR occur on planar reefs that are concentrated north of 16° S and between 21 and 22° S, including almost all (97.6%) vegetated cays and low wooded islands. Importantly, approximately 60 percent of planar reefs presently do not support reef islands, and reef islands are not restricted to planar reefs. For example, 42 unvegetated cays occur on reef patches. Figure 21.2 shows the distribution of the major types of reef island on the GBR. More than 70 percent of reef islands on the GBR are unvegetated cays, with most located north of Cairns. They are also particularly common on the Swain Reefs between 21 and 22° S. A few unvegetated cays are located on the outer reefs (eg Sand Bank numbers 7 and 8), but only where protection exists[70]. Unvegetated cays are not found between Wheeler Reef in the central GBR south to the northern Pompey Reefs (a distance of 315 km). This absence probably reflects the high tidal range (approximately eight metres near Broad Sound; see section 21.3.1), and greater exposure to both normal and cyclonic waves on this section of the reef[70,127].

There are fewer vegetated cays than unvegetated cays on the GBR, but their distribution is similar. Most occur on planar reefs in the northern GBR, with a group of mostly larger vegetated cays located in the southern GBR (Capricorn Bunker Group). Vegetated cays also occur in the Swain Reefs and inner reefs in this area (Bell Cay and Bushy Island). No vegetated cays exist between Bushy Island, around 70 km east of Mackay, and Green Island offshore from Cairns, more than 600 km north.

***Figure 21.2*** *Distribution of different types of reef islands in the GBR (after Hopley et al.[82]). Isobase lines indicate approximate time when modern sea level was reached in panel a, and approximate tidal range in panel c.*



Several vegetated cays are located on the far northern outer barrier (Tydeman Cay, an unnamed cay on a reef at 13° 22′ S, Moulter Cay and Raine Island), but none exist on outer barrier islands outside this province. The distribution of complex low wooded islands is strongly associated with the location of smaller planar reefs with emergent reef flats that are concentrated on the inner shelf north of Cairns. Ninety-four percent are within 20 km of the mainland, and all lie west of (inside) the zero hydro-isostatic isobase and have experienced relative sea level fall since the mid-Holocene[21,71] (see section 21.3.1).

The confinement of GBR reef islands inside the zero hydro-isostatic isobase raises the question of whether relative sea level fall is required for reef islands to form. Kench et al.[89] suggested that some Maldivian cays began to accumulate prior to reef flats reaching sea level, and West Indian cays have formed where sea level has risen gradually to present since the mid Holocene and continues to rise[167].

Radiocarbon-dated fossil microatolls underlie many of the reef islands investigated on the GBR[106,147], suggesting that most developed after the reefs had reached sea level[18,21]. Reef islands on the Cocos (Keeling) Islands, Indian Ocean, similarly exist over fossil reef flat foundations that became emergent as sea levels fell during the late Holocene[170]. Dickinson[35] proposed that wave-resistant emergent palaeoreef flats strongly influenced the development of stable reef islands on many Pacific atolls, but acknowledged that less stable 'unpinned' reef islands are common on reef flats that remain flooded by lower tides.

If radiocarbon chronologies are correct, rapid sand production, delivery, and cay deposition occurred on many planar reefs of the GBR between 4000 and 3000 years ago, with only relatively minor modifications since. However, AMS radiocarbon dating of a sandy reef island in Torres Strait indicates that mid-Holocene ages may be an artefact of age determination on bulk sand samples; ages of molluscs indicate sustained incremental accretion of Warraber Island over the past 3000 years[172]. Island nuclei deposited during this earlier accumulation phase are often indicated by the presence of mature vegetation and greater soil development (eg Douglas Island and Masthead Island[63]), although Woodroffe and Morrison[169] found no clear relationship between soil development and age at Makin Island, Kiribati. Significantly, most stable reef islands form over reefs in or entering the *senile* stage of geomorphological development. Factors that promote reef advance through the evolutionary sequence are therefore important drivers of reef island formation. Reef island formation has not ceased on the GBR, and new reef islands will form if reef growth and sediment production continues. Excluding the ribbon, incipient fringing and true fringing reefs (which are not easily accommodated in Hopley's[70] morphogenetic classification), about 26 percent of reefs on the GBR are planar, 13 percent are lagoonal, 12 percent are cresentic, 21 percent are patches and 27 percent are submerged (Figure 21.1). Average estimates of the time required to progress through this sequence were discussed in the preceding section, but we emphasise that small shallow lagoonal reefs can transform into planar reefs in as few as 250 years[82]. Thus, where sediment supply is adequate and reefs are of suitable elevation, geometry and energy exposure exist, reef islands may form quite rapidly.

Reef island morphology and location on a reef platform can be sensitive to changes in wave energy and direction, associated with both normal variability in ambient conditions and infrequent extreme events such as cyclones[47,48]. Island responses vary from total obliteration, shifts in size, shape and position, or shifts between predictable morphological states. Changes in sediment type, supply or erosion, and in the extent of lithification, may also modify reef island morphology[149,178]. Almost all descriptions of unvegetated cays on the GBR note that they can rapidly and markedly change shape, size, elevation and position[152,69,70,3]. Compact unvegetated sand cays are especially dynamic, with several disappearing in historical time. Hopley[70] reported the example of a cay on Pixie Reef, near Cairns that was about 45 metres in diameter in 1928, but had split into two cays 65 metres apart by 1929. Reef top sediments at Pixie Reef in the early 1980s were completely dispersed, with not even a discrete sand bar visible.

The most detailed account of compact unvegetated cay behaviour on the GBR exists for Wheeler Cay[69], a normally oval cay, around 80 by 50 metres in size, located over an area of sanded reef flat (170 by 250 metres). Between 1969 and 1977, including 1971 when Tropical Cyclone Althea struck, Wheeler Cay varied markedly in shape, size and location, moving over 11,000 square metres of reef flat during this period. The highest point on Wheeler Cay migrated as much as 13 metres in a day that included a three-hour storm with gusts to 60 knots, and the whole cay moved six metres on another day under light winds of less than 10 knots. Wheeler Cay had moved and changed shape again by 1980, but remained within the original sanded reef flat area[3].

The most stable reef islands typically occur on small to medium-sized reefs, with larger cays usually more stable than smaller ones. Vegetation is indicative of some stability and may also improve or maintain stability in various ways. Relatively large cays on the GBR are unvegetated compared to other reef areas in the world. For example, Waterwitch Cay is 2.8 hectares was unvegetated when visited in 1973, but all cays larger than 0.1 hectare on the Belize barrier are vegetated, and at Kapingamarangi Atoll all islets greater than 0.01 hectare support terrestrial plants[146]. This difference may reflect the larger tidal ranges, cyclone exposure, and possibly greater mobility of reef islands on the GBR. These constraints are particularly limiting on the central GBR.

Many stable reef islands are partially lithified, a process requiring at least temporary stability to occur[145,147], and which may impart improved stability in the longer term[137]. Beach rock is common on GBR reef islands, and forms a hard shoreline resistant to erosion. However, even large islands with extensive beach rock can be destabilised. For example, at Waterwitch Cay massive beach rock outcrops suggest previous periods of moderate stability, but at present the cay is barren, undoubtedly mobile, and disjunct from these lithified former shorelines. The cementation of cay sediments by phosphate solutions derived from guano to form phosphate rock is another lithification process that can improve reef island stability. Phosphate rocks mainly form above the high tide mark and in island interiors where birds may congregate. Where phosphate rock is well developed, such as at Raine Island, the island core becomes hardened and prospects for enduring island stability are improved, although unconsolidated beaches may remain dynamic.

### 21.2.3 High island beaches and spits

More than 600 high islands – continental outcrops separated from the mainland when the sea flooded the continental shelf after the last ice age – occur within the GBR. Many high islands have beaches, particularly in leeward embayments. Some of these beaches are fringed by reef and dominated by carbonate sediments (eg northwest end of Curacoa Island). Others are dominated by terrigenous sediments and have no fringing reef offshore (eg Horseshoe Bay, Magnetic Island). Beach rock is common on carbonate rich beaches, with lithified sediments varying from sands through to coarser shingle and rubble.

Many high islands, especially in the central GBR, have large leeside spits, many features of which are similar to the low wooded islands. The spit at Dunk Island, for example, extends more than 1200 metres along its central axis. Spit morphology is generally consistent with wave refraction around the islands and surrounding reefs. Most spits are dominated by terrigenous sediments, including boulders deposited during high-energy events. Hopley[73] concluded that larger spits were not Holocene deposits, but were multi-generational features formed over several previous sea level highstands. The soil development and elevated interiors of many spits are compatible with greater antiquity and formation during previous highstands when sea levels were higher than at present[94]. Many of these higher surfaces are well vegetated, and phosphatised (eg Dunk Island). Holocene carbonate deposits are also associated with several spits, with some developing prograding sequences of shingle ridges

(eg Curacoa Island and Rattlesnake Island). These ridges preserve a history of severe (greater than category 3) cyclone impact extending back to the mid-Holocene. These records show that severe storms affect most places on the GBR on average every 200 to 300 years, and that this recurrence interval has not significantly varied for the past 6000 or so years[61]. Nott and Hayne[120] have argued that this recurrence interval is significantly shorter than that calculated from instrumental records (and used in IPCC climate change projections), and suggests severe storms occur frequently enough to significantly influence coral communities and reef development.

### 21.2.4 Mainland sandy coastlines

Much of the mainland coast inside the GBR is sandy, composed of siliciclastic sediments derived from coastal catchments. Most of the sandy coastline may be geomorphologically described as either beach ridge plain or coastal sand barrier, with coastal dunes locally associated with both. Beach ridges are coastal sand ridges emplaced by waves, with sequences developing as successive ridges are emplaced on a prograding coast[150,151]. The mechanisms of beach ridge formation are debated, with pulsed sediment supply[2] and storm emplacement[119] the two main theories. Barrier systems may be broadly described as coastal sand deposits worked onshore by the transgression, but separated from the hinterland by an estuary or wetlands.

Beach ridges trail north from the mouth of almost every stream along the coast, typically forming a plain around 500 metres wide of up to 10 ridges. Much wider sequences have developed adjacent to major rivers. At the Haughton River, for example, a beach ridge plain of greater than 100 ridges is more than five kilometres wide. Beaches on exposed parts of the central Queensland coast typically develop a steep, coarse-grained, reflective upper profile and a lower gradient, fine-grained, dissipative lower profile. North of Cairns, wave energy is reduced because the barrier reef is closer. Sandy beaches with narrow beach ridge plains (generally less than one km) separated by rocky headlands occur along this coast. Most beach ridges on the GBR coast are Holocene in age, but some remnants of Pleistocene barriers exist[65].

High wave energy and lower tidal ranges are normally associated with barrier development, but more than 30 barrier systems occur on macrotidal sections of the central Queensland coast. Further north, near Kurrimine, a multiple barrier system up to 12 km wide occurs, in which at least three phases of progradation can be recognized from the orientation of ridge crests[56]. Ridges exposed to prevailing south-easterly winds commonly develop a dune cap, with higher ridges developing at the north of exposed beaches.

Several of the largest coastal dune fields in tropical Australia occur on Cape York, especially at Newcastle Bay, Orford Bay, Cape Grenville (400 km$^2$), Cape Flattery (700 km$^2$), and Cape Bedford. These dune fields are located where weathering of Mesozoic sandstone yields abundant sand, and the coast is exposed to south-easterlies that mobilise them during the dry season. Elongate parabolic dunes up to 5 kilometres long and over 100 metres high have developed which are now largely, but not fully, stabilised beneath heath or rainforest. Large dunes, rising to 60 metres, also occur on the northern end of Hinchinbrook Island. Smaller dune fields occur further south on Whitsunday Island, Curtis Island, and north of Yeppoon. Weathering features indicate that larger dune fields are of considerable age, formed during previous sea level lowstands[128,101].

Most of the beach ridge and barrier systems on the mainland GBR coast underwent a phase of active accretion and progradation during the late-Holocene[56], which did not continue to present in some locations. For example, mangrove muds of 2000 to 3000 years age interpreted as being originally deposited in the lee of seaward beach ridges now locally outcrop on exposed sections of the central and northern GBR coasts[175]. These muds have been uncovered by coastal retreat, which clearly should not be assumed to be a recent phenomenon, or anthropogenically forced.

Carbonate sediments occur on beaches adjacent to mainland fringing reefs, which are mainly concentrated around the Whitsunday Islands and further north around Cape Tribulation. Carbonates are subordinate to siliciclastic sediments even at these locations. Massive beach rock like that on offshore reefs and high islands may form where carbonates are well represented, such as at Hydeaway Bay in the Whitsunday region, but is relatively uncommon.

### 21.2.5 Mainland muddy coastlines

Muddy shorelines on the mainland coast are most common in north-facing bays protected from the prevailing south-easterly winds. In these areas the inshore sediment prism, a body of fine sediment trapped in the nearshore zone, can encroach onto the shoreline. On exposed coasts resuspension prevents the landward edge of the prism extending further inshore than the five metre isobath[97]. A series of characteristic geomorphological zones develop on these muddy coasts[42] (see chapter 9). Broad salt flats usually dominate the supratidal and upper intertidal, with freshwater marshes developing in higher rainfall areas. Sequences of shelly or coarse sandy ridges (known as cheniers) occur on many salt flats, a legacy of episodic cyclones in these normally low-energy environments[19,8]. At Princess Charlotte Bay, Chappell et al.[21] estimated that storms capable of depositing a chenier have occurred about every 80 years since the mid-Holocene. Near Sandfly Creek in Cleveland Bay (central GBR) at least four ridges can be identified within one kilometre of the active mangrove muds. The rear ridge is around 3700 years old and the most seaward 1400 years old, yielding a late Holocene progradation rate of about 0.5 metres per year[17]. Seaward of the salt flats a mangrove fringe usually occurs, the exact elevation of which varies locally. At Cocoa Creek, near Townsville, it lies between the mean low and high water spring tide levels[173]. Seaward of the mangroves are broad bioturbated mudflats, often with significant seagrass meadows. Tidal creeks incise back into the salt flats in many areas. Heap et al.[62] provide excellent descriptions of many of these systems on the GBR coast.

Chronostratigraphic studies suggest that these environments have typically developed as mangroves colonised the shoreline in the later part of the transgression and migrated landward with sea level until the mid-Holocene highstand. Seaward migration of the living mangrove fringe and salt flat development over the earlier mangrove deposits then occurred as sea levels fell to present during the late Holocene. Muddy shorelines are impressive sinks of fine sediment on the inner GBR, and as discussed by Lovelock and Ellison (chapter 9), they are major nutrient stores. Sedimentation patterns on muddy coastlines may vary according to the relative importance of tidal currents and terrestrial runoff in sediment supply, and thus climate and sea level changes may significantly affect sedimentation in mangrove forests and adjacent salt flats[162].

## 21.3 Exposure and sensitivity to major climate change stressors

### 21.3.1 Sea level rise

### *21.3.1.1 Post glacial sea level history.*

Understanding sea level history is important for evaluating the vulnerability of the GBR to climate change for several reasons. First, detailed sea level histories can inform interpretations of how future sea level changes on the GBR might differ from predicted average global rates. Second, they provide a context for interpreting previous reef development and how reefs may respond to future change. Third, identification of features formed at higher sea levels, such as emergent palaeoreef flats[35] (section 21.2.2), allows recognition and consideration of physiographic regions and possibly process thresholds for inclusion in climate or sea level change response models. Reported rates of historical and future sea level change are generally global averages derived from a globally aggregated instrumental data set. A rate of rise around 1.7 mm per year is typically quoted for the past century, accelerating since 1993 to around 3 mm per year[25]. Assessments of the exposure and sensitivity of geomorphological features of the GBR to possible future sea level changes should consider the regional pattern of relative sea level change as this is the sea level signal to which the system will respond. Regional and global signals may differ due to a variety of mostly dynamic earth (isostatic) and ocean (temperature, density, wind and atmospheric pressure) factors.

The precise details of elevation and chronology vary spatially, but sea level was close to present by around 6500 years ago along much of the inner GBR, before rising a further metre or so by 6000 years ago and then falling to its present level[68,21]. Subtle flexure of the continental shelf in response to loading with seawater during the postglacial transgression (hydro-isostasy) produces this pattern[115]. Hydro-isostatic flexure occurs about a hinge line (the zero isobase[20]), to the east of which the shelf has subsided and relative sea level has risen, and to the west of which the shelf has flexed upward and relative sea level has fallen. This history has two major implications for assessments of future vulnerability. First, the inner GBR has experienced relative sea level fall for several thousand years, with intertidal communities formed in the mid-Holocene often elevated around a metre above their modern equivalents[21]. Second, different locations across the shelf have different sea level histories that may affect their response to future climate changes[71,115].

Geomorphological responses to postglacial sea level changes prior to the mid-Holocene highstand are also relevant to vulnerability assessments. During the last deglaciation at least two periods of rapid and sustained sea level rise forced by ice-sheet decay and melt-water discharge occurred. The two best-known events are melt-water pulse 1A (MWP-1A) and melt-water pulse 1B (MWP-1B)[46,4]. MWP-1A is accepted as ‘a real feature of the postglacial eustatic sea level history’[159], beginning about 14,500 years ago, after which sea level rose by 40 to 55 mm per year for around 500 years[46]. The details of MWP-1B and other melt-water pulses[179,26,10] are less certain[138,6,174]. Reef growth on the GBR was limited to the continental slope during both MWP-1A and 1B by low sea levels, and thus they did not affect the contemporary GBR. Shelf reefs had established by 7600 years ago, but no convincing evidence of the melt-water pulse speculated then exists on the GBR[82]. Although direct evidence from the GBR is lacking, reefs clearly survived rapid sea level rise during MWP-1 events at Barbados and Tahiti[46,5], confirming the capacity of healthy reefs to endure sustained episodes of sea level rise at rates exceeding those predicted for the next century.

### 21.3.1.2 Tide range and wave exposure

The sensitivity of geomorphological environments to sea level changes in the order of millimetres per year is influenced by the variability of the ambient water level signal to which they are adjusted. Generally, ‘noisy’ environments – such as where waves and or tidal range are high – are less sensitive (Lovelock and Ellison chapter 9). Within the GBR, tidal range varies with latitude and across the shelf, ranging between 3.6 and 2.5 metres from Torres Strait to Cairns, but exceeding eight metres at Broad Sound on the southern GBR coast (refer to Figure 21.2c). The spring tidal range at the shelf edge is typically about three metres. The present-day wave climate is similarly variable, with smaller waves where the outer barrier is best developed and where fetch inside the barrier is limited. The hydrodynamics of the GBR are summarised in detail in Hopley et al.[82]. We emphasise that contemporary conditions are not always the same as those that have prevailed in the past, or during important periods of ecosystem or geomorphological development. For example, Hopley[73] suggested that boulder beaches and spits inside the central GBR were reworked by larger waves during the ‘Holocene high-energy window’ – a short interval in the mid-Holocene when the outer barrier lagged sea level and oceanic waves entered the GBR lagoon. Tidal ranges within the GBR have also been modified as sea level, reef, and coastal configurations changed through time.

### 21.3.1.3 Other background sea level variability

Superimposed over longer-term sea level fluctuations, and shorter ones such as tides, are other ocean-atmosphere phenomena with a range of frequencies and amplitudes, such as the El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation, and the Interdecadal Pacific Oscillation. For example, sea level in the Western Pacific can oscillate by about 0.5 metres as the ENSO shifts from El Niño to La Niña over cycles as short as four to six years[177,60]. Such variations are another source of natural variability that may temper sensitivity to slower rates of predicted sea level change.

### 21.3.1.4 Depth range, bathymetric relief and topography

The exposure and sensitivity of geomorphological features will vary according to the breadth of the depth range in which they form. For example, coral reefs capable of flourishing within a 30 to 50 metre depth window are less sensitive to rising seas than reef islands, which form and persist within a much narrower vertical range. Especially on low gradient parts of the GBR, it is important to recognise that marked lateral shoreline translations may accompany sea level rise. In some areas shorelines may simply migrate across similar deposits emplaced in the late Holocene, but complex re-organisation of the coastal zone may ensue elsewhere.

## 21.3.2 Rising sea surface temperature

The exposure and sensitivity of geomorphological features on the GBR to rising sea surface temperature (SST) will mainly be influenced by the thermal regime presently experienced, whether projected increases will be mitigated or made worse at various locations, and the sensitivity of key biota to thermal stress. Broad regional variations in SST within the GBR are summarised in chapters 2 and 17. Rising SSTs may affect some geomorphological processes such as cementation and lithification by increasing the speed of reactions, but thermal stress of key organisms – which will vary between groups, and between and within species – will be the main impact.

Thermal stress will not be uniform across the GBR, or across habitats at smaller scales (eg reef front compared to lagoon). It will vary according to tolerances developed in response to the present-day thermal regime, with tolerance to three–day hot spells most critical for coral bleaching[9]. The magnitude and rate of temperature changes over the past century may also be important (Lough chapter 2, Lovelock and Ellison chapter 9, Fabricius et al. chapter 17), with corals in the south of the GBR experiencing warming by 0.7°C since 1903 – almost double the 0.4°C experienced on the northern GBR[64] (Fabricius et al. chapter 17). This geographic difference is further revealed by comparison of the mean maximum SST for both the northern and southern GBR for 1910 to 1919 and 1990 to 1999. This analysis shows a 0.6°C SST rise on the southern GBR but no change in the northern GBR (Lough chapter 2).

Surface water heating is the main cause of thermal stress, and greatest exposure occurs where surface waters are weakly mixed by waves and currents, have longer residence times, and do not receive cooler upwelling. However, it is important to note that for coral reefs, for example, bleaching is most highly correlated with three–day hot spells rather than mean or median conditions[9], and thus only short-term exposure is required for significant stress impacts to occur. At smaller scales, organisms living where water may stagnate, such as in enclosed embayments, lagoons or ponded reef flats, may experience more critical stresses than on reef fronts and flanks where active hydrodynamic mixing takes place. The physiologically damaging effects of ultraviolet-A and ultraviolet-B radiation[164] will also vary spatially due to mediation associated with hydrodynamic mixing and water column properties. Inshore turbid zone reefs may be less exposed than those in clearer waters where damaging radiation can penetrate to greater depths[78].

The sensitivity of different organisms to rising SSTs is a common theme in preceding chapters. Geomorphological features that rely directly or indirectly on 'sensitive' organisms to produce materials, or to undertake or facilitate important geomorphological processes are most exposed and sensitive to these impacts. The sensitivity of most features has not been adequately established, but coral reefs are an obvious example. Corals have bleached repeatedly in recent decades due primarily to elevated SSTs, and projections suggest that the capacity of reefs on the GBR to maintain significant coral communities will be largely lost as SSTs rise[40]. Although this outcome may be catastrophic ecologically, and will inevitably produce some geomorphological modification, the medium- to long-term geomorphological significance of these changes remains unquantified. With other stresses (eg acidification, increased storm frequency) rising SST will probably lead to increased mortality and availability of a new pulse of sediment on many reefs (see Sheppard et al.[139]).

### 21.3.3 Increased cyclone activity

Tropical cyclones have two major impacts on geomorphological features of the GBR: i) direct damage through storm waves, and ii) extreme cyclonic rainfall that generates floods delivering freshwater, sediments and nutrients to the GBR (exposure and sensitivity to rainfall are discussed in section 21.3.4). Tropical cyclones can devastate coral and other communities, but they are important constructional events for several geomorphological features. Storm blocks, shingle ramparts, and detrital facies are common geomorphologic features that document a long-history of storm exposure on the GBR[136]. Cheniers and beach ridges along the mainland coast similarly record episodic cyclone impacts in the recent geological past[119]. Severe tropical cyclones have occurred about once every 200 to 300 years on average for the last 6000 or so years over most of the GBR[24,61,120], and these events may be mechanically destructive to depths below 20 metres[155].

Many tropical coastal habitats are adapted to periodic cyclonic disturbances, with robust communities and structures in higher-energy settings better able to physically withstand periodic cyclonic impacts[27]. Exposure to physical destruction by cyclone waves thus tends to show strong cross-shelf variation, being lowest where reef configuration limits fetch and/or attenuates waves as they cross the shelf. However, this decline in exposure occurs against a corresponding increase in sensitivity. Corals on inshore reefs tend to have weaker skeletons and can be less firmly attached to the reef structure. The reef structure may also be weakly consolidated[142,125], and potentially more sensitive and vulnerable to damage.

An increase in the destructiveness and intensity of cyclones in recent decades has been argued and linked to climate change[44,160], although the completeness of the underlying data is questioned[95,96]. Increased cyclone activity will raise the exposure of more frequently affected reefs. The physical sensitivity of structures should not vary markedly from the present-day pattern in the short term, but accompanying changes in community structure are predicted which may have variable effects. Reefs dominated by fragile forms will be most sensitive initially, but as community structure changes and massive and encrusting corals with a higher probability of surviving wave damage dominate[39], this effect may diminish. Geomorphological features reliant on sediments produced by fragile assemblages will be sensitive to this structural transformation. Coral shingle is an important contributor to many geomorphological features (eg ramparts and beaches), and with a high surface area to volume ratio may be a major and relatively dynamic producer of coral sands. Projected general reductions in calcification and simplification of coral communities may significantly modify sediment budgets, especially where post-event community recovery slows and the interval between storms shortens. Under this scenario, geomorphological features that have historically been constructed by cyclones may be eroded in the longer-term future.

Patterns of exposure and sensitivity for inter- and supratidal geomorphological features like reef islands and sandy beaches differ from those of reefs, and are likely to be affected more by factors such as tidal range and late Holocene sea level history. For example, many reef islands on the inner northern GBR are located over emergent reef platforms (see section 21.3.1), and are protected by lithified ramparts. These islands are less exposed and sensitive to changed cyclone activity than unconsolidated cays on lower reef flats. By their very nature, sandy beaches are sensitive to changes in hydrodynamic environment and sediment supply, and move toward an equilibrium profile that is largely a function of these two parameters.

### 21.3.4 Enhanced rainfall

Climate change projections suggest that increased cyclone activity will produce more frequent high intensity rainfall events against a more general drying of most coastal catchments (Lough chapter 2). This change may expose geomorphological features to three interrelated impacts: i) increased frequency of freshwater flood plumes, ii) increased delivery of sediments to the coast, and iii) increased exposure to elevated nutrients and contaminants. Inshore geomorphological features will be most exposed, however as these environments have been episodically affected by similar events in the past their sensitivity should be relatively low. However, water quality has declined historically in many parts of the inner GBR[33,11,45], and it is uncertain whether past resilience to plume impacts has been maintained.

More frequent large plumes may extend further offshore and increase the exposure of offshore reefs. Cyclonic rain produced a large flood plume from the Fitzroy River in 1992 that lowered salinity over shallow reefs on the Keppel Islands and reduced live coral cover by 85 percent[155]. The sensitivity of inshore communities other than coral reefs have been discussed in other chapters, and will affect the sensitivity of associated geomorphological features such as sandy or muddy coastlines. As an example, reductions in mangrove or seagrass cover may affect patterns of sediment deposition, erosion and transport[70,154].

Changes in both sediment availability and transport potential may affect sediment delivery to the coast. Terrestrial and marine records in the region indicate that sediment yields are highest when dry conditions are followed by episodic high intensity rain events, especially where drought reduces vegetation cover and increases catchment vulnerability to erosion[103]. The sensitivity of inshore communities to increased supply of fine sediments should be low, as they already experience high turbidity due to wind and wave resuspension of the inshore sediment prism[98,99]. Where excessive sediment is delivered, currents may struggle to transport it all away and some smothering may result. This is most likely in sheltered locations, or near stream mouths[163]. Where flood plumes deliver suspended sediments beyond their present range, sensitivities may be higher. Delivery of sand to the coast may also increase, but this will take longer, and the amount of new sediment delivered will still be relatively small compared to the amount accumulated over the last 6000 years[97]. Sands are unlikely to be transported far offshore, but may be redistributed alongshore[7,126], possibly renewing beach ridge progradation in some areas.

### 21.3.5 Reduced rainfall

A major impact of reduced general rainfall but episodic high intensity events will be reduced vegetation cover and an increase in terrestrial erosion, with accompanying water quality reductions if nutrient and contaminant yields during floods remain high. The sensitivity of geomorphological features to reduced rainfall will also be influenced by the extent to which attributes such as vegetation that rely on regular freshwater are involved in enhancing stability or other important processes. For example, where insufficient rain falls to replenish aquifers or keep vegetation alive, cays may become more vulnerable to erosion, or less likely to become vegetated with the stability that brings.

### 21.3.6 Ocean acidification

Atmospheric carbon dioxide ($CO_2$) concentrations are expected to rise from pre-industrial levels of 280 parts per million to 540 to 970 parts per million by 2100[86] (Lough chapter 2). Carbon dioxide entering the ocean reduces the capacity of calcifying organisms to produce calcium carbonate skeletons[131], with obvious potential impacts for geomorphological features reliant on these materials. Future changes in seawater pH are anticipated to reach levels not experienced for several hundreds of millions of years[16]. Critically, carbonate ion availability is estimated to fall below that necessary for calcification by corals when atmospheric concentrations of $CO_2$ exceed 500 parts per million[50,58] (Hoegh-Guldberg et al. chapter 10), a level at the lower end of future projections.

It has been argued that negative impacts of ocean acidification on calcification will be offset by positive impacts of temperature increases on the same process[107]. Although calcification is highly correlated with temperature in GBR corals[102], it is unlikely that this would persist in a warming world[93].

## 21.4 Potential impacts, adaptive capacity and vulnerability

Predictions of the potential impacts, adaptive capacity and vulnerability of projected climate change on geomorphological features of the GBR are complicated by the diversity of each of the major geomorphological features, and uncertainties regarding the nature of projected climate changes, geomorphological responses, and of synergistic effects of climate change, natural variability and human activities. Nonetheless we can be certain that the entire GBR and adjacent coast experienced massive and repeated environmental changes beyond anticipated projections in the recent geological past, as glacial-interglacial cycles forced sea levels through more than 100 metres of vertical range, and forced shorelines to migrate laterally over tens of kilometres. The adaptive capacity of most geomorphological features – even under sub-optimal conditions – is therefore self evident, and the long-term vulnerability of many would appear demonstrably low. However, confidence in this conclusion is reduced where biological productivity is important and the survival of critical organisms is threatened by climate driven changes, compounded by pressures associated with other anthropogenic activities. Coral reefs are clearly in this category.

In this section we infer the adaptive capacity of major geomorphological features from knowledge of their morphological behaviour to natural cycles (some with limits that exceed the extremes of future projections), including those observed from outside the GBR and those that have occurred in the historical and geological past.

### 21.4.1 Coral reefs

#### *21.4.1.1 Sea level rise*

Potential impacts of climate change on the geomorphological structure of coral reefs are summarised in Table 21.2 and schematically shown in Figure 21.3. Despite earlier concerns, the consensus is now that rising sea levels alone will not present significant difficulties for healthy reefs, as projected rises are within the range of natural variability and geological precedent. Projected rates of sea level rise are well below published rates of coral growth, which are commonly around 10 to 12 mm per year for massive corals and as high as 180 mm per year for branching species[22]. However, coral and reef growth rates are not synonymous. Reef accretion – the rate at which the reef grows vertically – is not only a product of coral calcification, but is also affected by factors including sediment production by other reef organisms (eg foraminiferans, molluscs, etc), bioerosion, and sediment redistribution[84]. Spencer[144] calculated average rates of vertical accretion for the northern, central and southern GBR at 14, 10, and 12 mm per year respectively, again suggesting that projected sea level rise will not be problematic for healthy reefs.

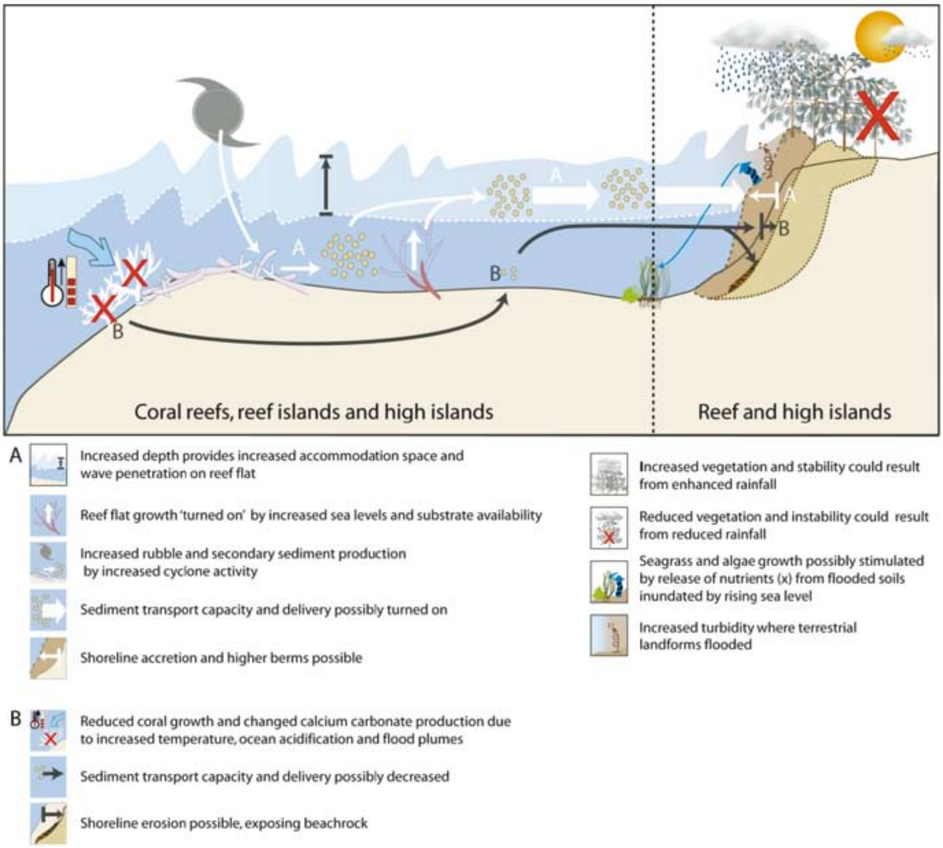
Many reefs on the GBR reached sea level in the mid-Holocene[82], after which continued vertical and luxuriant reef growth was 'turned off' by stresses associated with a lack of accommodation space[14]. Hopley[77] argued that where coral growth rates have not been diminished by human activities, the more rapid projections of future sea level rise (0.5 metres by 2100) may reinvigorate or 'turn on'[14] at least some of these reefs by providing new accommodation space into which they may grow. Kinsey and Hopley[90] estimated that the current calcification rate of about 50 million tonnes per year on the GBR may increase to 70 million tonnes per year if presently senescent reef flats are recolonised. Production declines at depth due to rising sea level are unlikely to be significant.

***Table 21.2*** *Potential impacts of global climate change on coral reef geomorphological features of the GBR*

| Process(es) or Parameter(s) affected | Potential impact | Important factors |
|---|---|---|
| **Rising sea level** | | |
| Water depth<br>Inundation extent<br>Sediment transport and deposition<br>Substrate availability<br>Water quality | Lower irradiance for deeper corals and possibly slower growth or even 'drowning'<br>Increase accommodation space into which depth-constrained reef communities may extend<br>Shoreline retreat may present additional habitable substrate<br>Flooding and erosion of terrestrial landforms may elevate inshore turbidity, nutrient and contaminant loads<br>Greater depths and openness on the inner GBR may improve flushing and water quality in some areas<br>Increased depth and potential for wave-generated sediment transport across shallow reefs | Rate of rise critical[77]<br>Tidal range relative to rise rate<br>Late Holocene sea level history important<br>Turbidity impacts |
| **Rising sea surface temperature** | | |
| Community structure<br>Photosynthesis/ Autotrophic activities<br>Calcification rates and contributing calcifiers<br>Primary production<br>Erosion (including bioerosion) and disease<br>Reef strength | Increased coral bleaching and loss of sensitive species<br>Coral reef calcification rate and sediment budget modified (composition, texture, amount, and durability of sediments)<br>Reef growth rate may change – construction may shift more to detrital than framework growth<br>Balance between primary calcification production and secondary sediment yield may be modified<br>Increased bare substratum for colonisation by algae and accessible to disease and bioeroders<br>Physical strength of coral reef structures reduced, and stability as substratum for colonisation possibly altered | 0.8°C rise causes bleaching, 2 to 3°C rise causes coral death<br>Three-day hot spells are most critical for corals, not average temperature increases[9]<br>Genotypic variation (coral and zooxanthellae) in sensitivity<br>Ameliorating factors (eg upwelling) and warming patterns (enclosed lagoons etc) will affect spatial patterns |

| Process(es) or Parameter(s) affected | Potential impact | Important factors |
|---|---|---|
| **Increased tropical cyclone activity and surge** | | |
| Wave climate and exposure | Greater exposure to larger waves<br>Physical destruction of corals and other living benthos<br>Shifts toward more storm tolerant taxa and modification of sediment types and rates of production<br>Increased erosion and secondary sediment production<br>Episodic production and transport of coral rubble/shingle<br>Reduced structural complexity, strength and possibly long-term wave resistance | Existing exposure to high energy storms and associated geomorphological characteristics<br>Tide range and reef depth relative to wave base<br>Skeletons weakened by bioerosion, crystal poisoning, etc, more vulnerable |
| **Enhanced rainfall** | | |
| Fluvial and groundwater inputs into GBR lagoon<br>Runoff quality<br>Inshore water quality<br>Salinity<br>Coral reef growth | Increased number, duration and extent of flood plumes<br>Reefs further offshore affected more often by flood plumes<br>Increased delivery of sediments, nutrients and contaminants by flood plumes<br>Increased benthic algae and reduced coral cover<br>Increased probability of low salinity mortality events in enclosed lagoons, moats and settings with restricted circulation and mixing<br>Increased bioerosion | Proximity to mainland and/or larger high islands<br>Catchment size and land use |
| **Reduced rainfall** | | |
| Inshore and surface water salinity<br>Inshore water quality | Reduced number, duration and extent of flood plumes<br>Offshore water conditions occur closer to the coast, possibly causing shifts in community composition and change to fewer heterotrophs<br>Reduced delivery of sediments, nutrients and contaminants by flood plumes<br>Increased coral cover<br>Reduced bioerosion | Proximity to mainland and/or larger high islands<br>Catchment size and land use |
| **Ocean acidification** | | |
| Calcium carbonate production and fixing | Reduced coral and other biotic calcification | Full ramifications likely to be significant but limited knowledge |

*Figure 21.3* Key processes and potential impacts of predicted climate changes on coral reefs, reef islands and high islands



Rapid rates of sea level rise will improve transmission of wave and current energy over reef surfaces, producing several effects. Depth is a critical control of energy available for sediment transport, which is likely to increase over reef flats as sea level rises. The inner part of the wide reef flat at Warraber in the Torres Strait is now around one metre above the live reef as a result of regional hydro-isostatic adjustment[171], similar to many reef flats inside the zero isobase on the GBR[71,115]. Recent work by Kench and Brander[87] showed that the reef flat at Warraber is geomorphologically inert for most of the time at present, with waves above 0.05 metres occurring on the outer reef for less than 30 percent of each spring neap tidal cycle. Larger waves will propagate further across the reef flat over a larger proportion of the tidal cycle under higher sea level scenarios. Where sediments are available, either residual from earlier production or as reinvigorated primary production, they may be more efficiently transported by the increased wave energy. This may benefit both the maintenance and growth of geomorphological features composed of detrital materials such as reef islands and beaches, and primary production of carbonate where sediment accumulation is limiting (ie where sediments are smothering substrates suitable for productive communities).

### 21.4.1.2 Rising sea surface temperature

Projected sea level rise may have some positive outcomes for reefs, but it is increasingly unlikely that they will outweigh the negative impacts of other climate change stressors. Rising temperatures are predicted to cause more widespread, severe, and frequent bleaching (Hoegh-Guldberg et al. chapter 10), resulting in reduced live coral cover and structural complexity, and modified reef sediment budgets. Branching *Acropora* corals are likely to be affected first and gradually decline, but massive corals will be increasingly affected as SSTs continue to warm (Hoegh-Guldberg et al. chapter 10). Diminished coral cover and fecundity of survivors will reduce recovery of bleached communities, producing an increasingly bare substratum dominated by fleshy algae[34]. The general decline in Acropora and other primary framework builders will reduce primary reef framework construction; fewer living *Acropora* and reduced shingle sediment production will be amongst the most rapid changes. However, the dynamics are complex; it has been argued that warmer sea surface temperatures will (up to a limit) produce faster growth but lower calcification[107,108,93], so that material produced is more fragile and easily broken down[139]. More shingle will initially be produced as declining thickets are disturbed more often, leading to at least a short period of accelerated reef evolution as lagoons are infilled by detrital sediments, however diminished recovery and thicket growth will ultimately reduce the production of this material.

Some reefs may shift toward an erosional regime, with unstable frameworks and reduced structural integrity, but again such effects are likely to be variable. Well-preserved reef surfaces and even corals formed thousands of years ago (eg fossil microatolls) suggest that this may be a very slow process and not a major problem in many areas. Conversely, however, fringing reefs in the Seychelles are now far less efficient dissipaters of wave energy than they were prior to the 1998 bleaching event and subsequent coral mortality and disintegration[139].

### 21.4.1.3 Increased cyclone activity

Increased cyclone activity will have variable effects, with negligible impact on reefs or reef habitats in high-energy settings, but potentially large impacts on those not adapted to such events. Reefs composed of unbound detrital material, as is common for many inshore reefs[142], are vulnerable to stripping and possibly structural collapse. As for other climate stressors, the negative effects of community composition changes will be reinforced by slow and increasingly limited recovery between events. Resultant morphological changes are likely to mirror those associated with rising SSTs, with initial loss of fragile components. This loss may be hastened by skeletal weakening associated with eutrophication and crystal poisoning (where contaminants are incorporated into the skeletal structure and reduce skeletal strength[130]). Greater bioerosion associated with increased benthic algae and plankton may also increase the rate of coral loss. The diminution of coarse primary carbonates to sands may be accelerated by these processes, but not enough is known to confidently predict this outcome.

Although corals are important components on most healthy reefs, other organisms are also significant contributors to reef construction (section 21.2). As coral vigour is reduced by climate change stress, other contributors, for example, molluscs, foraminiferans or coralline algae may compensate if suitable substrates and conditions are available. *Halimeda*, for example, has formed large banks in areas of the GBR affected by nutrient rich upwellings[41], and may become a more widespread and significant contributor to reefs affected by eutrophication. Nutrients released as soils were reworked

by rising seas after the last ice age were linked to flourishing *Halimeda* by Hopley[76], and are a useful analogy for possible future changes. Carbonate sediments produced by different organisms vary markedly in important properties like durability and hydrodynamic behaviour, and shifts in producers can alter sediment transport and depositional dynamics. The impacts of such changes on various reef environments are poorly understood.

### *21.4.1.4 Enhanced rainfall*

Increased exposure to low salinity flood plumes fed by enhanced rainfall may cause greater mortality than occurs at present, but the most significant impacts of a changed hydrological regime will probably be associated with increased nutrient and contaminant loads rather than freshwater runoff *per se*. Modern reef growth occurred as the coastal plain was actively prograding (eg Belperio[7], Graham[56]), suggesting that floods themselves are unlikely to limit reef growth.

### *21.4.1.5 Ocean acidification*

Increased ocean acidification will pose a critical threat to continued reef development as calcifying organisms, particularly those secreting aragonite, struggle to form skeletons[131]. Kleypas et al.[91] suggested that doubling pre-industrial $CO_2$ by 2050 would lower the ocean's aragonite saturation state by 10 to 30 percent, with dire consequences for reef construction. How these changes will affect existing reefs is uncertain. Existing reefs will remain as geological structures, but the probability of continued vigorous reef growth seems low. Ecological and aesthetic reef values will also likely be diminished as detrital sediments increasingly dominate.

## 21.4.2 Reef islands

The potential impacts of climate change on reef islands of the GBR will, like the islands themselves, be diverse. Anticipated potential impacts are summarised in Table 21.3 and schematically presented in Figure 21.3.

### *21.4.2.1 Sea level rise*

Early concerns that sea level rise will simply drown reef islands have been shown to be incorrect, with island response being the result of the complex interplay of a variety of physical, biological and chemical factors. Changes in sediment production and delivery must be considered, and the possibility that some islands will actually expand, at least in the short to medium term, is now widely accepted[106,75,77,88].

Rising sea level may improve sediment transport across reef platforms by allowing larger waves to propagate further through more of each tidal cycle (section 21.4.1.1). Inner shelf reefs experienced a relative sea level fall of about a metre during the late-Holocene, allowing sediments to build up over reef flats that are immobile except during storms. Shallow depths over these reef platforms limit sediment transport and delivery to reef islands[77,87], and rising sea levels might ameliorate this impediment by allowing more wave energy across the reef platform. Hopley[75] suggested that a sea level rise of just 0.5 metres would remobilise reef flat sediment deposits and move them shoreward. Many reef geomorphologists agree that projected sea level rise will substantially re-work unconsolidated sediments, at least enough to maintain reef island mass[104,75,88].

***Table 21.3*** *Potential impacts of global climate change on reef island geomorphology of the GBR*

| Process(es) or Parameter(s) affected | Potential impact | Important factors |
|---|---|---|
| **Rising sea level** | | |
| Water depth<br>Inundation extent<br>Sediment transport and deposition, erosion<br>Reef island stability | Increased accommodation space for reef communities to grow into<br>Increased depth and potential for wave-generated sediment transport across shallow reef flats<br>Larger waves possible at reef island shores, with greater shoreline modification<br>Higher berms<br>Changed reef island morphology | Rate of rise critical[77]<br>Tidal range relative to rise rate<br>Late Holocene sea level history important<br>Degree of lithification will mediate effects<br>Vegetation will stabilise<br>Likely to be regional patterns |
| **Rising sea surface temperature** | | |
| Community structure<br>Calcification rates and contributing calcifiers<br>Sediment production<br>Erosion (including bioerosion)<br>Reef construction<br>Reef strength | Increased coral bleaching<br>Reduced coral calcification and modified sediment budgets (composition, texture, amounts, and durability of sediments)<br>Reef growth rate may change – construction may shift more to detrital than framework growth<br>Balance between primary calcification production and secondary sediment may be modified<br>Increased bare substratum for colonisation by algae and accessible to disease and bioeroders<br>More rapid diminution of sediment size<br>Structural integrity reduced, and stability as substratum for colonisation altered<br>More rapid cementation of beach materials | 0.8°C rise causes bleaching, 2 to 3°C rise causes coral death<br>Three-day hot spells appear most critical for corals rather than average or median temperature increases[9]<br>Genotypic variation (both coral and zooxanthellae) in sensitivity<br>Ameliorating factors (eg upwelling, etc) and probably warming patterns (enclosed lagoons, etc) will affect spatial patterns |
| **Increased tropical cyclone activity and surge** | | |
| Wave climate and exposure<br>Depth during cyclones increased by surge | Greater exposure to larger waves<br>Physical destruction of corals and other living benthos – production of reef rubble, shingle, sands and finer sediments<br>Shifts toward storm tolerant taxa and modification of the types and rates of sediment produced<br>More erosion (including bioerosion) and increased secondary sediment production<br>Episodic transport of coral rubble/shingle<br>Reduced structural complexity, strength and long-term wave resistance<br>Inundation and higher level erosion during surge events<br>Higher berms | Existing exposure to storms<br>Tide range and reef depth relative to wave base<br>Shelf bathymetry and coastal configuration will affect surge potential<br>Complexity of reef network will affect fetch and capacity for longer period waves to develop<br>Reef platform shape will affect wave refraction and influence sediment dispersion versus concentration properties of storm waves |

| Process(es) or Parameter(s) affected | Potential impact | Important factors |
|---|---|---|
| **Enhanced rainfall** | | |
| Fluvial and groundwater inputs into GBR lagoon<br>Runoff quality<br>Salinity<br>Freshwater aquifers<br>Establishment and survival of reef island vegetation | Increased number, duration and extent of large flood plumes<br>Reefs further offshore affected more often by flood plumes<br>Increased delivery of sediments, nutrients and contaminants by floods<br>Increased benthic algae and reduced coral cover<br>Increased bioerosion and disease<br>Increased low salinity mortality events in enclosed lagoons, moats and poorly mixed settings<br>Improved reef island stability where vegetation establishment and survival improved<br>Reduced reef island mobility and vulnerability to climate variations | Significant local variation likely between GBR catchments<br>Proximity to mainland and island size<br>Nature of sediment delivery complicated – first flush, higher vegetation cover possibly reducing catchment sediment yields – depends on nature of rainfall increase – even increase or extreme event |
| **Reduced rainfall** | | |
| Inshore and surface water salinity<br>Freshwater aquifers<br>Establishment and survival of reef island vegetation | Reduced number, duration and extent of flood plumes, but possibly more very large ones<br>Offshore water conditions occur closer to the coast, possibly causing shifts in community composition and change to fewer heterotrophs<br>Improved autotrophic calcium carbonate production<br>Increased sensitivity to episodic floods<br>Reduced delivery of siliclastic sediments, nutrients and contaminants by flood plumes<br>More difficult for island vegetation to establish and survive and reduced potential for vegetation enhanced stability<br>Islands more mobile and vulnerable to storms and climate fluctuations such as wind shifts etc | Significant variation likely between GBR catchments. Nature of sediment delivery complicated – first flush, higher vegetation cover possibly reducing catchment sediment yields – depends on nature of rainfall increase – even increase or extreme event |
| **Ocean acidification** | | |
| Calcium carbonate production and fixing | Reduced calcification<br>Reduced primary production of carbonate sands and reef island sediments<br>Possible that increased erosion of standing reef framework may initially yield higher secondary reef sediments | Full ramifications likely to be significant but limited knowledge<br>Surface area to volume – will smaller sediments, like sands, which dominate many reef islands, be aggressively dissolved? |

Once sediments stored on reef flats are exhausted by transfer to the reef island or possibly off reef, the amount of new sediment available will depend on the rate of sea level rise if current calcification rates in different geomorphologic zones can be sustained. Hopley[77] modelled carbonate budgets for an idealised atoll reef flat responding to a 0.5 and 1.8 metre rise by 2100, and demonstrated that almost all reef zones would vertically accrete and reef morphology would not change if sea level rose at the more modest rate. However, the algal zone transformed to coral cover at the higher rate of rise, and calcium carbonate production substantially increased. Some of this enhanced carbonate productivity would yield sediments suitable for reef island construction, and because greater depth allows waves competent to transport sediments shoreward to occur more often, Hopley[77] concluded that a higher rate of sea level rise may ironically be more beneficial for reef island sustainability than a slower rate.

Cay build-up is largely controlled by the characteristics of waves reaching the beach, with berm height – the height of the beach above mean high water – dependent on wave run-up. Run-up increases with wave height, wave steepness, beach slope, shape of the beach profile and roughness and permeability of the beach material. Gourlay and Hacker[55] found that wave run-up height varied reliably with the ratio of the breaker height to water depth over the reef flat at Raine Island, because wave heights are limited by shallow water breaking conditions. They indicated that the height of the four metre beach berm was controlled by the wave run-up height during the highest spring tides. Gourlay and Hacker[55] calculated that with a 0.6 metre rise in sea level, 1.6 metre waves could reach the cay, and would increase berm height from 4 to 4.8 metres, and that 0.5 metre waves reaching the cay at lower tides would increase berm height by 1.2 to 5.2 metres. These results reveal that reef islands may vertically accrete by an amount larger than the sea level rise if the reef flat lags and larger waves can reach the beach.

Although residual sediment may be stored on emergent reef flats (due to both their greater elevation and relative age), the positive benefits of sea level rise depend on increased reef flat depth, which will take longer to manifest on higher reef flats. Interactions between the buffer against rising sea levels afforded by late Holocene emergence and the timing of re-invigoration of reef flat sediment transport and productivity are fundamental to accurate predictions of reef-island response to climate change, but are poorly known and require further investigation. Sea level changes may also modify reef-top habitats and the contributions of different carbonate producers, affecting the rate of sediment delivery to reef islands, and thus reef island dynamics.

### *21.4.2.2 Reduced carbonate production*

Several studies suggest that cays in the GBR and Torres Strait accumulated most of their mass prior to 2000 years ago, with only limited accretion since[13,166]. On the northern inner GBR this early phase of accretion corresponds with the generally more substantive and elevated inner island core, which is usually replete with soils and mature vegetation. A lower peripheral terrace is associated with recent accretion[147]. Whether the distinction between these two surfaces is a function of sediment supply or falling sea level (and thus reduced sediment delivery to the island) is unresolved, but both possibilities are closely connected. Chronological data are available for very few islands. Those that are available and the terraced morphology evident on others suggest that many cays of the inner GBR: i) are formed of sediments produced several thousand years ago, ii) appear to have accumulated a significant proportion of their bulk long ago, and iii) have not received significant recent carbonate

production. Projected collapses in carbonate productivity may thus have limited immediate impact on these islands, especially as many are significantly lithified which should improve resistance to erosion if sediment deficits arise.

It would be unwise to assume that all reef islands on the GBR have developed as described above, or that they have similar potential resilience to climate-change impacts. As indicated, GBR reef islands are geomorphologically diverse, the geomorphologies of few are known in detail, and establishing reef island accretion chronologies is technically difficult. For example, Lady Elliot Island has continued to accrete at a relatively constant rate since the mid-Holocene[24], and similar chronology has recently been established for Warraber based on selective Accelerator Mass Spectrometer radiocarbon dating of gastropod sediments[172]. Gastropods inhabit the reef flat close to the island, and derived sediments are transported quickly onshore so that death and depositional ages are close. This new chronology suggests that Warraber has grown at a reasonably constant rate since the mid-Holocene[135], differing from a previous chronology based on dating bulk sediment samples which suggested rapid accretion soon after the mid-Holocene and relative senescence thereafter[166]. A comparable accretion history was determined for Makin, Kiribati by Woodroffe and Morrison[169]. An important difference between Makin and Warraber however, is that Makin is mainly composed of foraminiferans produced on the outer reef flat that are quickly moved onshore.

This close connection between outer reef flat production and reef island accretion occurs at Makin despite partial emergence of the reef-top during the late Holocene. Woodroffe and Morrison[169] implied that sea level fall may have initiated rather than impeded reef island growth by creating abundant foraminiferan habitat and presenting a slightly elevated foundation over which foraminiferan sediments could accumulate. Yamano et al.[178] determined that foraminiferans are also the main contributors of recent sediment at Green Island on the GBR, and suggested that this dominance arose because relative sea level fall in the late Holocene increased foraminiferan habitat and reduced that of other carbonate producers. Earlier sedimentological work by one of the authors (DH) at Green Island indicates that foraminiferans are a very recent addition to cay sediments (see Hopley et al.[82]). Green Island is actually inside the zero-isobase and thus has not experienced relative sea level fall inferred as the driver for expanded habitat and representation of foraminiferans at this location. Nevertheless, modern foraminiferans at Green Island also live near the reef edge, with tight coupling between foraminiferan production and delivery to the cay attributed to the hydraulic traits of foraminiferan tests, which are relatively easy to entrain and transport[178].

Where reef islands are younger, the future may be less positive. Sediments comprising these islands have probably been produced more recently on reef flats nearer to sea level than those on the inner shelf. Lithification to form beach rock and conglomerate will aid stabilisation, but they are nonetheless more vulnerable to climate change in several ways. First, the reef flats on which they form are deeper than those of the inner shelf, and thus the islands are more sensitive to changes in wind and wave conditions, including those that may move sediments off the reef platform. Shoreline mobility associated with this sensitivity can also inhibit lithification and longer-term stability. Second, less sediment is likely to be stored on these reef flats for reworking toward the islands as sea level rises. Finally, active carbonate production and reef island accumulation are more tightly coupled on less emergent reef flats, with efficient transfer of products to the zone of accumulation. In these circumstances diminished carbonate productivity and sediment supply will have more immediate effects on island sediment budgets and morphologies.

Reef islands near the zero isobase are particularly vulnerable to these effects, as are those where the tidal range is relatively large (allowing larger waves across reef flats at neap and higher tides) or where the outer barrier provides less protection from large waves. That these conditions limit reef island development and stability is demonstrated by the lack of reef islands through the central GBR (section 21.2.2). Bushy Island (20° 57′ S, 150° 05′ E) is an exception, able to endure because it is located inside the zero isobase on an elevated reef flat encircled by a large algal rim and moat that mediates the destabilising effects of high tidal range and wave exposure[70].

### 21.4.2.3 Increased cyclone intensity

The impacts of increased cyclone intensity are difficult to predict, as the relationship between geomorphologic work and cyclone intensity is poorly understood. Changes in cyclone duration and frequency may be more significant. Cyclones have clearly caused significant erosion on some reef islands, especially unvegetated cays (section 21.2.2) but they can also be important accretion events. On Lady Elliot Island, concentric ridges increase in age toward the island interior and document the progressive growth of the island during storms[24]. On the northern GBR, storm-emplaced features such as shingle islands, and shingle and rubble ramparts are common on the low wooded islands[147,148]. Materials must clearly be available for accretion to occur, and hence cays on reefs where carbonate productivity has declined and sediment supplies have become limited are most vulnerable to erosion during cyclones.

Broad spatial patterns of vulnerability to cyclone impacts may be inferred from observations of contemporary patterns of island occurrence, mobility, and stability. Islands of the inner GBR located over emergent reef flats are least vulnerable. Many are protected by lithified ramparts, conglomerates or beach rock outcrops and a metre or so of emergent, often sediment veneered, reef which buffers the negative impacts of rising sea level and or reduced carbonate production. However, inshore reefs are potentially exposed to higher storm surges than those further offshore, which could offset this buffer. Storm surge on mid-shelf and offshore reefs is usually small, for example, the surge produced by cyclone Emily in 1972 (central pressure 985 hectopascal) at Gladstone was two metres but at Heron Island, over which it directly passed, the surge was less than 0.8 metres[66].

As noted above, reef islands are rare through the central GBR, and climate change will not enhance their prospects for development in this area. In the southern GBR, more intense cyclones may affect reef island formation and stability in areas such as the Swain and Pompey Reefs. Here, a complex reef network impedes the development of discrete focal points for wave refraction and island accumulation under prevailing south-easterly winds. Reef islands in these areas appear particularly vulnerable to disturbance by cyclones approaching from variable directions that may redistribute sediments over the reef top and require a long time to recover. Many cays in the Capricorn Bunker group lie on more symmetrical reef platforms and have developed on well-confined focal points. Several are large, well vegetated, and partially lithified by both phosphatisation of sediments in the island interior and beach rock formation on the shoreline. Although the present high mobility of the distal tails of the more elongate cays will continue and possibly increase, the long-term stability of these islands is good.

### *21.4.2.4 Changed rainfall patterns*

Changed rainfall regimes will have different impacts depending on island size. Higher rainfall on small, mobile, arid islands presently lacking a freshwater lens may improve prospects for vegetation establishment and stability. This benefit would be reduced if rainfall remains highly seasonal or mainly associated with extreme events. Reduced rainfall will be problematic for vegetation survival, and possibly reduce stability of islands with freshwater aquifers requiring regular recharge. According to the layered aquifer model of reef island ground water retention[15], a threshold island width of 120 metres is needed for a freshwater lens to develop. Oberdorfer et al.[122] suggested that if island size remains above this level, rising sea level has a counter intuitive effect on the total freshwater resource of islands possessing a layered aquifer. An increase in sea level makes available more low permeability Holocene materials for freshwater retention, increasing the total freshwater resource. Hence, a rise in sea level may not be disastrous for island ground water resources, but may actually increase if islands become larger, especially if rainfall also increases.

## 21.4.3 High island beaches and spits

The potential impacts of climate change on high island beaches will be similar to those on reef islands and mainland sandy coasts (Table 21.4, Figure 21.3). Only specific differences are described in detail here.

### *21.4.3.1 Sea level rise*

Most high islands on the GBR are west of the zero isobase and have experienced late Holocene emergence. Many have developed broad leeward reef flats over which spits have accumulated. Beaches are most common on leeward embayed shorelines. As on reef islands, rising sea level will increase depth and wave penetration across shallow inshore areas, mobilising and transporting stored sediments shoreward. Larger waves will run-up higher on the beach, producing an increase in berm height that may exceed the rise in sea level if adequate sediment is available[55].

The interiors of large spits are often elevated up to several metres above peripheral Holocene deposits, and inundation of higher surfaces is unlikely in the short to medium term. However, if they were flooded, nutrients may leach onto the reef flat[23]. Leached nutrients may boost algal and seagrass growth, possibly affecting coastal sediment dynamics. Seagrass meadow expansion on the reef flat at Green Island trapped sediments on the reef flat and reduced sediment supply to the cay beach, causing erosion[70,154].

### *21.4.3.2 Reduced carbonate production*

Where sea level rises quickly, presently unproductive reef flats may be recolonised by calcifiers and carbonate production may increase[77], although as discussed for coral reefs and reef islands, if projections of ocean acidification are correct calcifying organisms will struggle to survive[93]. Rising SSTs and increased bleaching will affect coral community structure, but the geomorphologic impacts are difficult to predict. Sheppard et al.[139] showed that wave energy at the beach increased due to a loss of reef structure caused by bleaching mortality, but many fringing reefs on the GBR have persisted without significant accretion for several millennia and still appear structurally robust[143].

***Table 21.4*** *Potential impacts of global climate change on high island spit and beach geomorphology of the GBR*

| Process(es) or Parameter(s) affected | Potential impact | Important factors |
|---|---|---|
| **Rising sea level** | | |
| Water depth<br>Inundation extent<br>Sediment transport and deposition<br>Water quality | Increased accommodation space for reef communities to grow into<br>Shoreline retreat may present additional substrate for colonisation by coral reefs<br>Flooding and erosion of terrestrial landforms may elevate inshore turbidity, nutrient and contaminant loads<br>Increased depth and potential wave-generated sediment transport across shallow reefs<br>Mobilisation of reef flat or shallow inshore sediments<br>New 'high-energy window'? Period when many spits in the central GBR were reworked | Rate of rise critical[77]<br>Tidal range relative to rise rate<br>Late Holocene emergence provides a buffer |
| **Rising sea surface temperature** | | |
| Community structure<br>Calcification rates<br>Sediment production | Impact on coral beaches with increased bleaching events as carbonate sediment budget<br>Modified primary sediment production – change in dominant producers of sand-sized carbonate sediments<br>Increased bare surface for algal colonisation – possible switch to mollusc dominated sediments? | 0.8°C rise causes bleaching, 2 to 3°C rise causes coral death<br>Three-day hot spells appear most critical for corals rather than average temperature increases[9]<br>Genotypic variation (both coral and zooxanthellae) in sensitivity |
| **Increased tropical cyclone activity and surge** | | |
| Wave climate and exposure<br>Depth during cyclones increased by surge | Significant erosion of beach and backing dunes or land<br>Loss of beach and erosion buffer<br>Physical destruction of corals and reef<br>Episodic production and transport of coral rubble/shingle<br>Higher spit mobility/lower stability<br>Larger waves at reef island shores, greater shoreline modification<br>Exposure of beachrock or other cemented deposits | Frequency and intensity of storm events impacts will affect recovery<br>Some smaller spits and exposed beaches may erode beyond point of recovery<br>Sediment characteristics and availability will be important controls |

| Process(es) or Parameter(s) affected | Potential impact | Important factors |
|---|---|---|
| **Enhanced rainfall** | | |
| Fluvial and groundwater inputs into GBR lagoon<br>Runoff quality<br>Salinity<br>Freshwater aquifers<br>Establishment and survival of littoral vegetation | Increased number, duration and extent of large flood plume<br>Reefs further offshore affected more often by flood plumes<br>Increased delivery of sediments, nutrients and contaminants by floods<br>Increased benthic algae and reduced coral cover<br>More low salinity mortality events in enclosed lagoons, moats and poorly mixed settings<br>Increased bioerosion<br>Improved chances of vegetation establishment and survival<br>Improved spit and beach stability | Significant variation likely between GBR catchments. Nature of sediment delivery complicated – first flush, higher vegetation cover possibly reducing catchment sediment yields – depends on nature of rainfall increase – even increase or extreme event |
| **Reduced rainfall** | | |
| Inshore and surface water salinity<br>Freshwater aquifers<br>Establishment and survival of reef island vegetation | Reduced number, duration and extent of flood plumes, but possibly more very large ones<br>Offshore water conditions occur closer to the coast, possibly causing shifts in community composition and change to fewer heterotrophs<br>Improved autotrophic calcium carbonate production<br>Increased sensitivity to episodic floods<br>Reduced delivery of siliclastic sediments, nutrients and contaminants by flood plumes<br>More difficult for littoral vegetation to establish and survive and reduced potential for vegetation enhanced stability<br>Spits more mobile and vulnerable to storms and climate fluctuations such as wind shifts etc | Local variation likely between GBR catchments<br>Proximity to mainland and island size<br>Nature of sediment delivery complicated – first flush, higher vegetation cover possibly reducing catchment sediment yields – depends on nature of rainfall increase – even increase or extreme event |
| **Ocean acidification** | | |
| Calcium carbonate production and fixing | Reduced calcification<br>Reduced primary production of carbonate sands and reef island sediments<br>Possible that increased erosion of standing reef framework may initially yield higher secondary reef sediments | Full ramifications likely to be significant but limited knowledge<br>Reduction in carbonate production and representation in features |

In the Seychelles, Sheppard et al.[139] noted that many reef flats had become rubble dominated, and this may occur on some GBR fringing reefs as sands are preferentially winnowed. Greater wave access across reef flats under higher sea level may increase spit mobility, particularly at distal unconsolidated ends, and especially during storms. Some lithification is common if spit or beach sediments contain significant carbonate, with beach rock or conglomerate often exposed. These indurated deposits improve stability, but they can be outflanked and stranded off the active beach. Where sediment supply is exhausted and shorelines retreat, lithified shorelines resist erosion more effectively than unconsolidated deposits. However, shorelines dominated by lithified deposits may not provide critical ecosystem services formerly satisfied by unconsolidated beaches, such as turtle nesting habitat.

#### *21.4.3.3 Changed rainfall patterns*

Modified rainfall regimes have several potential impacts on bigger islands with larger catchments and creeks. Extreme floods fed by more intense cyclones may lead to episodic salinity stress near creek mouths, although this would be localised and rare. If rainfall generally declines but extreme events become more frequent, vegetation cover may decline and sediment yields increase, possibly compensating for reduced carbonate productivity in some areas.

### 21.4.4 Mainland sandy coasts

Close links between form and process are confirmed by morphodynamic studies of many Australian sandy beaches[140], including several on the mainland coast inside the GBR[112,113]. These studies typically relate beach morphology to incident energy (wave and tide) and sediment supply and traits. Characteristic beach states develop for a given set of conditions, and beach state will change if conditions are altered[176,141]. Adjustments can occur over short timeframes at a local scale in response to events such as storms. However, longer-term studies are needed to detect more protracted cycles of erosion (cut) and accretion (fill)[105], and the influence of climatic events such as the El Niño-Southern Oscillation and the Interdecadal Pacific Oscillation at sub- and multi-decadal scales[129,52,53]. These influences must be filtered when reconstructing coastal change trajectories based on short records, and it is equally important to accommodate changes within these cycles in vulnerability assessments.

#### *21.4.4.1 Sea level rise*

The impacts of sea level rise on sandy beaches have traditionally been assessed using the simple two-dimensional Bruun Rule[12], which states that a beach will adjust its cross-shore profile to maintain an equilibrium form in response to a given sea level rise. This rule implies that sand moved from the upper beach is deposited lower on the profile as equilibrium adjustments are made, with limited loss to seaward. Various modifications of this basic rule have followed in subsequent years, including several that support Bruun's calculation that the ratio of shoreline recession to sea level rise is usually within the range of 50 to 200:1[100]. However, the application of the Bruun Rule as a universal predictor of beach response to sea level rise has been criticised[28]. Problems with its application to mainland sandy beaches inside the GBR include: the arbitrary selection of closure depth; it does not account well for rock outcrops; sediment deposition on land is not included; the impacts of storms are not accommodated; and longshore transport, complex currents, and the timeframe of sediment transport

are all ignored. Particular issues inside the GBR arise where morphological adjustment is not possible because the lower shoreface is lithified beach rock or conglomerate, or where hard reef flats lie offshore of the beach[88].

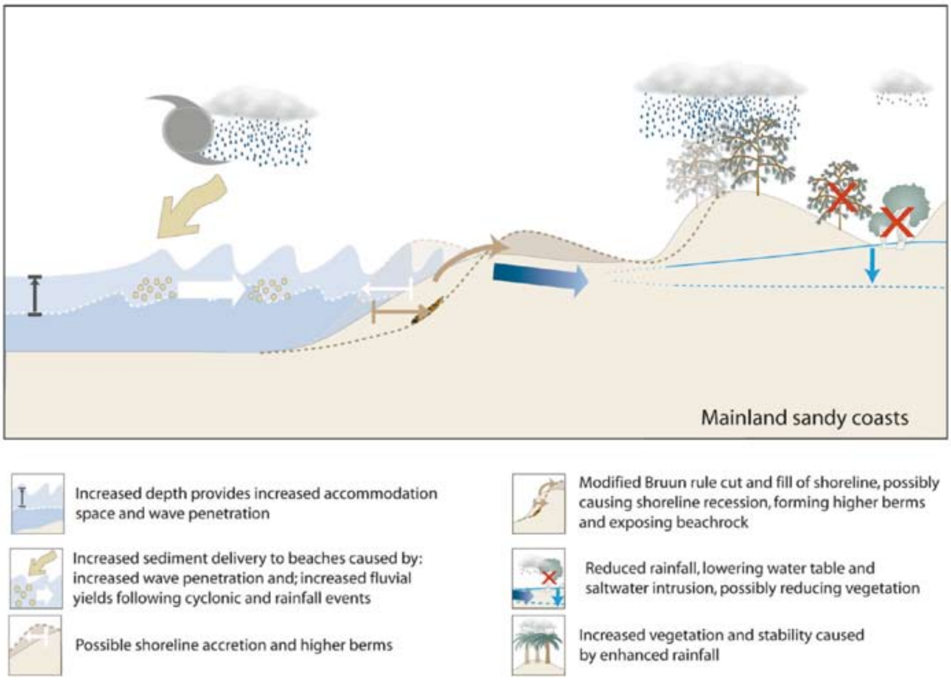
In the shorter term, rising sea levels will probably cause some coastal retreat as sediments are worked onshore by wave swash. Responses will vary with tidal range, exposure to wave energy, and sediment supply. The main potential impacts are summarised in Table 21.5 and Figure 21.4. In assessing the significance of any changes, it is important to note that shoreline recession over the past few millennia has been a common trend on many sandy coasts inside the GBR[175,142]. Isolating the impacts of climate change induced retreat from this longer erosion trajectory, and the various other cycles and events that may cause shoreline variation discussed earlier, is challenging. Although many beach ridge sequences have been eroding for the past few thousand years, most began to form around 6000 years ago[65,56], and large sand reserves remain onshore at most locations.

***Table 21.5*** *Potential impacts of global climate change on mainland sandy coast geomorphology inside the GBR*

| Process(es) or Parameter(s) affected | Potential impacts | Important factors |
|---|---|---|
| **Rising sea level** | | |
| Water depth<br>Inundation extent<br>Sediment transport and deposition<br>Water quality | Morphodynamic adjustment of beach form<br>Loss of beach width and beach amenity<br>Elevated impact of waves<br>Inundation of coastal lowlands<br>Intrusion of saline water into freshwater sandy aquifers | Bruun rule applicability limited on GBR<br>Late Holocene emergence on coast and significant progradation since mid-Holocene provides a buffer |
| **Rising sea surface temperature** | | |
| Carbonate production | Minor potential impacts on carbonate rich beaches as bleaching events reduce primary carbonate productivity | Few beaches carbonate rich |
| **Increased tropical cyclone activity and surge** | | |
| Wave climate and exposure | Significant erosion of beach and backing dunes or land<br>Loss of beach width and beach amenity<br>Loss of beach and erosion buffer<br>Exposure of lithified shorelines<br>Change to coarser beach<br>Loss of nesting habitat | Energy difference between storm events and ambient conditions may hinder recovery to equilibrium form<br>Storm frequency and intensity affects time available for beach recovery |

| Process(es) or Parameter(s) affected | Potential impacts | Important factors |
|---|---|---|
| **Enhanced rainfall** | | |
| Vegetation cover<br>Terrigenous sediment yield and delivery | Increased supply of siliclastic sediments to the coast<br>Altered vegetation coverage of sand coloniser plants | Significant variation likely between GBR catchments. Nature of sediment delivery complicated – first flush, higher vegetation cover possibly reducing catchment sediment yields – depends on nature of rainfall increase – even increase or extreme event |
| **Reduced rainfall** | | |
| Vegetation cover<br>Terrigenous sediment yield and delivery | Reduction in coastal sediment supply<br>Altered vegetation coverage of sand coloniser plants | Significant variation likely between GBR catchments. Nature of sediment delivery complicated – first flush, higher vegetation cover possibly reducing catchment sediment yields – depends on nature of rainfall increase – even increase or extreme event |

***Figure 21.4*** *Key processes and potential impacts of predicted climate changes on the geomorphology of mainland sandy coasts*



### *21.4.4.2 Increased cyclone intensity*

How mainland sandy coasts will respond geomorphologically to changes in cyclone intensity is unclear, and the potential impacts of more intense cyclones are thus difficult to predict. For example, severe Tropical Cyclone Larry (category 5) directly struck Mission Beach in March 2006 but caused only minor geomorphological change (personal observations), whereas a large proportion of North Queensland's sandy coast was significantly eroded during Tropical Cyclone Justin in 1997 (category 3). Justin was a large cyclone system that persisted for three weeks, including two spring tide phases[111]. The geomorphological impacts of cyclones on sandy shores vary according to many factors, but the stage of the tide (including storm surge) at which the cyclone strikes, the duration of cyclone activity, the size of the cyclone system, and sediment supply are among the most important.

Cyclone impacts can be significantly amplified by storm surge on the mainland coast, raising water levels and wave activity into higher parts of the coastal system less resilient to wave forces (eg dunes). Potential storm surge varies according to storm characteristics and paths (increasing with cyclone intensity – or as central pressure decreases – and as the approach direction is more perpendicular to the coast[118], but coastal configuration and offshore bathymetry also markedly affect surge height. Broad shallow bays with gently sloping offshore bathymetries generally produce the largest surge. Storm surges with calculated return periods of 100 years are around two metres above Australian Height Datum (AHD) north of Cairns, more than 4.5 metres above AHD at Broad Sound, and about three metres above AHD near Gladstone[82]. Models of surge with future climate change generally show the same spatial pattern, but suggest surge heights will increase by about one metre in the next century (eg Gutteridge, Hoskins and Davey[59]). Wave run-up also raises water levels and the zone of cyclone impact further above the shoreline. Inundation during several category 5 cyclones on the Western Australian coastline between 1998 and 2002 demonstrated run-up may add an extra 35 percent to surge elevation, and that erosion occurred to this level, not just that of the surge[121]. Central and southern parts of the GBR coast, where the outer reef is well offshore and waves are generally larger, are most vulnerable to these impacts under climate change scenarios.

### *21.4.4.3 Changed sediment supply*

Where sediment supply is limited, sandy shorelines will erode during intense cyclones. However, where deposits exist to be mobilised by cyclonic waves and currents, they may be moved onshore, and a cyclone may be an accretionary event. It has been argued that beach ridges – an important geomorphological feature of sandy coasts inside the GBR – may form in this way[119] (section 21.2.4). If rainfall patterns are modified as predicted, sand supply to the coast may increase due to reduced vegetation cover and episodic but erosive rainfall events and floods. The dynamics of sediment availability and transport to the coast will vary with catchment physiography and hydrological response. If sufficient sediment accumulates inshore, a phase of coastal progradation may re-establish in some areas.

Siliciclastic sediments dominate mainland beaches inside the GBR. Carbonates are well represented on beaches behind some fringing reefs, but are still subordinate to siliciclastics. Where carbonates are a significant component, changes in the productivity of calcifying organisms may modify the supply of carbonate sediments. If projected increases in ocean acidification eventuate, continued supply of carbonate sediments to mainland beaches could be threatened. The most probable outcome for most mainland sandy beaches of reduced carbonate production is a slow decline in carbonate representation and increase in the proportion of siliciclastics. Beaches with significant carbonate are generally located behind reefs and are relatively protected. Only minor changes in beach morphology would be expected because of changed sediment composition in these areas.

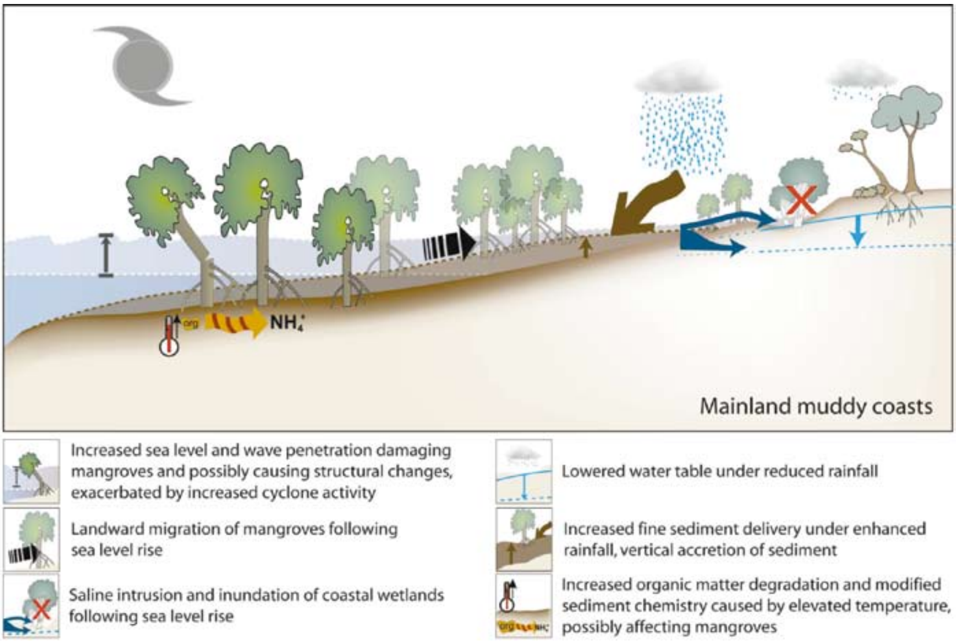
### 21.4.5 Mainland muddy coasts

Most mainland muddy coast inside the GBR occurs in north facing bays protected from the prevailing south-easterly winds. The geomorphology and potential impacts of climate change stressors are briefly outlined by Lovelock and Ellison (chapter 9), and are summarised in Table 21.6 and Figure 21.5.

***Table 21.6*** *Potential impacts of global climate change on muddy coastline geomorphology of the GBR*

| Process(es) or Parameter(s) affected | Potential impact | Important factors |
|---|---|---|
| **Rising sea level** | | |
| Water depth<br>Inundation extent<br>Sediment transport and deposition<br>Water quality | Increased erosion and sedimentation<br>Migration landward<br>Altered vegetation cover | Response will vary depending on the relative rates of sea level rise and sedimentation, ground water conditions, tidal amplitude and mangrove vigour<br>Late Holocene emergence on coast and significant progradation since mid-Holocene provides a buffer |
| **Increased tropical cyclone activity and surge** | | |
| Wave climate and exposure | Increased erosion<br>Saltwater inundation | Impact will vary with exposure, and degree stability or recovery affected by other climate change factors |
| **Enhanced rainfall** | | |
| | Altered nutrient and sediment budgets<br>Altered vegetation extent and coverage | Significant variation in present-day hydrological conditions in these systems between wet and dry tropics – may see shift in distributions. Dry tropics ecosystems more likely to be affected |
| **Reduced rainfall** | | |
| | Reduced environmental flow – increased salinity<br>Reduced sedimentation<br>Altered vegetation coverage | Wet tropics systems more likely to be affected |

***Figure 21.5*** *Key processes and potential impacts of predicted climate changes on the geomorphology of mainland muddy coasts*



### *21.4.5.1 Changed sediment supply and accretion*

The ability of mangrove shorelines to maintain their current positions and geometries varies with mangrove stand composition and tidal range. Mangrove shoreline migration is a function of the rate of sediment accretion relative to the rate of sea level rise, with responses likely to reflect local sediment dynamics and to be highly site specific[165]. Ellison and Stoddart[43] suggested that modern mangroves would erode if sea level rose faster than 0.9 mm per year, but as indicated above, sediment supply and accumulation rates must also be considered. Muddy coasts near larger catchments are more likely to receive sediment supplies adequate to keep pace with projected sea level rise, but the supply of sediments to the inner GBR should not be limiting, with catchment yields argued to have increased five to ten fold over the last few centuries[103]. Sediment cores from Bowling Green Bay reveal a distinctive mercury horizon three metres down core associated with the onset of gold processing in the upper Burdekin catchment just over a century ago[157]. Recent research in southeastern Australia suggests that sedimentation accounts for less than 50 percent of surface elevation variability in some mangrove-salt marsh systems[133], but this work is yet to be replicated in tropical Australia.

### *21.4.5.2 Sea level rise*

If sediment delivery is insufficient for vertical accretion to match sea level rise, mangrove communities and associated geomorphologic and ecological zones will probably migrate landward. Mangrove communities migrated rapidly landward as sea levels rose during the postglacial transgression[165], and continue to shift laterally where subsidence produces relative sea level rise today[134]. Along most of the mainland muddy shorelines of the GBR this migration entails mangrove retreat over sediments deposited as late-Holocene sea levels have fallen. The landward advance of mangrove and associated wetlands would progress unless impeded by anthropogenic or topographic structures, in which case zones will become compressed and possibly lost. This process is referred to as 'coastal squeeze' where coastal defence structures restrict horizontal migration[117]. Topographic gradients on most mainland muddy coasts are gentle, and thus modest sea level rise can affect large areas.

### *21.4.5.3 Increased cyclone activity*

Cyclones can have catastrophic and long-lasting impacts on mangrove communities and environments. Most of the muddy mainland coastline inside the GBR typically experiences low wave energy[82], but chenier sequences document a history of episodic cyclone strike and significant geomorphologic impacts[119]. Quantitative data on cyclone impacts on muddy coasts in northern Australia are rare[168]. The geomorphological impacts of Tropical Cyclone Althea, including the generally minor changes to muddy coasts were described by Hopley[67], but we are unaware of any research that has quantified the effects of individual cyclones on muddy coasts deposits on the GBR.

Observational accounts indicate that cyclone impacts can be patchy, but the emplacement of large cheniers several kilometres long shows that periodic disturbances and geomorphologic adjustments on a large scale do occur. However, the relationship between these deposits and storm history is poorly understood. Dated chenier sequences show that not all storms are recorded, possibly because shell beds that provide the sediments require adequate time to recover between events[19]. At Princess Charlotte Bay, this would appear to be around 80 years[21]. In contrast, coral shingle ridges at several locations on the GBR record severe storms with an average recurrence interval of around 200 years[61,120]. Given these frequencies, chenier plains should contain more cheniers than shingle ridge sequences contain ridges, but this is not the case. For example, the chenier plain at Cocoa Creek in Cleveland Bay contains eleven discrete cheniers but the shingle ridge sequence at Curacoa Island, around 75 km to the north, contains more than 20 discrete ridge units[61].

Mangroves play an important role in protecting coasts from high-energy events. However, as discussed for the other geomorphological features, the influence of more intense cyclones on these environments remains unclear. Recent category 5 Tropical Cyclone Larry did remarkably little damage to mangrove communities in Lugger Bay, reinforcing the earlier thesis that intensity is often not highly correlated with geomorphologic effectiveness. Tidal stage when a cyclone hits is probably the biggest factor influencing the geomorphological effect of cyclones at any location, with reduced effects if the cyclone arrives at lower tides. Storm duration, tide range and surge potential may also be important controls of the potential for geomorphological change, but this is yet to be determined.

## 21.5 Linkages

Where climate changes affect geomorphological features they will often be accompanied by ecological change, and in some instances, vice versa. Such linkages are too numerous to identify individually, and the details and significance of many are poorly known. Examples of several important linkages are outlined below.

Coral and framework loss will reduce habitat complexity and availability for many species, but as outlined in previous chapters these interactions are variable and multifaceted. There will be shifts in habitat, organisms and the rate and nature of carbonate produced. This will have flow through effects on rates of reef growth, growth fabrics, structural integrity and persistence.

Reduced reef growth and possibly increased destruction coincident with sea level rise may alter the wave climate within the GBR lagoon, potentially affecting the mainland coast. For example, ambient inshore wave energy may increase on open coasts as greater depth allows larger waves over the outer barrier, causing shoreline morphologies to change. Higher inshore energy may also affect water quality, with more resuspension and a wider distribution of turbid water than occurs at present.

Changed reef island dynamics will affect bird and turtle nesting success. This may be more complex than first envisaged. For example, increased mobility may reduce *Pisonia grandis* climax vegetation on many GBR cays. Loss of *Pisonia* would have serious implications for many birds, but other cays with rudimentary vegetation would still be important nesting sites (eg Michaelmas Cay). Reef islands with partially lithified shorelines may remain moderately stable if hydrodynamic, sedimentary and storm regimes change, but may lose unconsolidated beaches, with major implications for some nesting species. In contrast, unconsolidated cays may be highly mobile over reef platforms, but could maintain beaches suitable for nesting success.

## 21.6 Summary and recommendations

Climate changes will prove difficult if not catastrophic for many organisms on the GBR. However, major geomorphologic features have repeatedly survived large climate changes in the past, and will endure into the future, but possibly in a modified state. The history of the GBR (and other reefs globally) demonstrates a remarkable capacity for adaptation to significant change, driven both by external and internal factors. Many of the likely responses of geomorphological features on the GBR are not simplistic and require an understanding of geomorphological history and processes, which for many parts of the GBR is incomplete. Reefs grow, mature and may potentially enter a decay phase as part of a natural cycle on longer than ecological scales. An appreciation of where in this cycle a particular reef is, and how observed changes relate to this, is critical to effective documentation and management of climate change impacts.

At shorter time scales, the intrinsic capacity of many geomorphological features on the coast to adapt to changes in the physical environment will confer some resilience, but this may wane if poorly understood thresholds are crossed under sustained climate change pressure. The remarkable morphological diversity developed by the major geomorphological features within the GBR provides a significant buffer against catastrophic loss across the entire system. Nonetheless, parts of the GBR are vulnerable to global climate change not because of the changing climate alone, but because of additional stress factors – many of which relate to anthropogenic activities – that may lower the thresholds at which catastrophic change occurs. Some of these additional pressures, like reduced water quality, are local and regional issues that may be addressed by management at various government scales. Others, like ocean acidification, are global problems and will be far more challenging to overcome.

## 21.6.1 Key vulnerabilities to climate change

### *21.6.1.1 Coral reefs*

Ecological assessments of the adaptive capacity of GBR reefs in previous chapters concluded that offshore reefs in the northern GBR are least vulnerable to climate change, and those inshore and further south will be most affected. Geomorphological adaptive capacity will mostly be determined by the capacity of reef communities to produce sufficient calcium carbonate, or at the very least, for existing calcium carbonate products to be preserved. How carbonate production will change as communities change, and the immediacy and impact of these changes on coral reef geomorphology will be highly variable. Insufficient knowledge exists to confidently predict outcomes for even the simplest systems. Sheppard et al.[139] showed that responses can be rapid, but the geomorphology of many senile reefs on the GBR has changed little for millennia[70,21]. It is also possible that some reefs will be less vulnerable to some impacts of climate change due to changes in other parameters. For example, nearshore turbid reefs may be less vulnerable to the damaging effects of UV penetration, and the critical effects of SST may be mitigated around the submerged shelf edge reefs that may actually be exposed to cooler water if upwelling strength increases as has been predicted[82].

### *21.6.1.2 Reef islands*

Concerns that reef islands will disappear as climate changes are often based on misunderstandings of their morphodynamic sensitivity (relatively rapid morphological response to hydrodynamic and sediment supply conditions). Ironically, it is this sensitivity that confers on many GBR reef islands an intrinsic adaptive capacity to adjust to and often benefit from predicted climate changes. Reef islands will continue to move and be periodically removed by naturally variable climatic and sea level conditions, but it is likely that at least some GBR reef islands will, in the short term, adjust to rising sea levels, more intense cyclones, and modified rainfall regimes by getting larger and higher. This is especially so for reef islands on the inner GBR where relative sea level fell over the late Holocene, with sediments stored on emergent reef flats that may be mobilised and worked shorewards.

Many reef islands on the GBR are less vulnerable to climate change in the short term than popularly portrayed. However, variable responses will occur that largely reflect differences in reef platform elevation, sediment supply, and hydrodynamic setting, and thus regional patterns may be expressed. Definitive prediction of vulnerability requires a balanced assessment of i) antecedent buffers against negative impacts (eg residual sediment, lithification, platform emergence, vegetation), ii) the more immediate impacts of disturbances such as intense cyclones, and iii) the longer-term consequences of severely reduced new sediment production as a result of ocean acidification. Unvegetated cays on exposed reefs in areas of high tidal range are most vulnerable to sea level rise and will probably switch to an erosion phase at the lowest thresholds. Vegetated cays with lithified shores and interiors on emergent reefs platform are likely to be more resilient.

Insufficient data of adequate quality exist to systematically assess reef island vulnerability to climate-change stressors or their cumulative effects by 2100. However, all must be viewed as vulnerable if sea level rise continues beyond 2100 (expected even if climate is stabilised – Wigley's[161] 'sea level commitment'), or if extreme and rapid sea level rise occurs as may transpire, for example, if the West

Antarctic Ice Sheet melts[123]. Predicted rates of sea level rise are lower than rates during the postglacial transgression, but are considerably higher than historical rates[60]. Houghton et al.[83] calculated that predicted rates of sea level rise are 2.2 to 4.4 times that of the global average for the last century.

### 21.6.1.3 High island beaches and spits

Spits and high island beaches will adjust to the impacts of climate-change stressors, with both environments changing little. Some beaches and spits may become more mobile and dynamic, and higher but narrower. Backing dunes may be lost, reducing storm erosion buffer and beach amenity, but neither environment is particularly vulnerable to large modification.

### 21.6.1.4 Mainland sandy coasts

An important difference between the erosion impacts of tropical cyclones on tide-dominated beaches inside the GBR and storm impacts on wave-dominated beaches is that higher ambient energy levels enable the latter to recover relatively rapidly to an equilibrium or stable profile. In low energy settings recovery can be prolonged, and geomorphological changes caused by extreme events can persist for many years. Scarped beach ridges near Pallarenda (north of Townsville) produced during Tropical Cyclone Althea (category 3) in 1971 are still visible. If intense tropical cyclones become more frequent, the prospects for full geomorphologic recovery or achievement of a stable 'equilibrium morphology' between events is increasingly unlikely. Thus although morphodynamic adjustments of beach form to prevailing energy conditions provides some basis for adaptive capacity under future climate change scenarios, where extreme events do significant geomorphologic work and ambient energy conditions are inadequate to achieve a readjustment, the geomorphological condition of some sandy coasts may in the future reflect extreme events more than they do at present.

### 21.6.1.5 Mainland muddy coasts

The almost exclusive occurrence of mainland muddy coasts in protected north facing embayments and the low gradient topography they commonly develop makes them especially vulnerable to the more frequent occurrence of high intensity cyclones and, where accretion rates are low, to sea level rise. As discussed by Lovelock and Ellison (chapter 9), mangroves and other plants play an important role in protecting these normally low-energy environments from destructive storms, how these communities respond to climate change, and to modified disturbance and recovery regimes is not yet resolved. Any destabilisation of vegetation communities is likely to also affect geomorphological stability.

Muddy coasts adjacent to smaller catchments or those, perhaps ironically, not affected by anthropogenically elevated yields of terrestrial sediment, are most likely to receive insufficient sediment supply for vertical accretion rates to match sea level rise. Where accretion lags behind sea level rise shoreline translation will occur, potentially affecting important wetlands (including saline flats) at the rear of many of these systems. Changes in rainfall associated with climate change may put further pressure on these environments.

### 21.6.2 Potential management responses

This and other chapters have identified the particular vulnerabilities of the GBR to climate change. A common conclusion is that climate changes have happened in the past and that reefs have survived, but never before have they occurred in conjunction with a range of additional anthropogenic stressors that now also affect many reefs. It cannot be assumed that the GBR will survive these combined stresses as it has survived the impacts of previous climate change episodes. As indicated in section 21.6, some of the major effects and impacts of global climate change on the GBR, for example increased SST and ocean acidification, are global and require international intergovernmental co-operation and agreements to fully address. Given current intransigence by key governments, including Australia's, such agreements are unlikely to be achieved in the near future. Nonetheless, a range of management responses could be more quickly implemented for positive benefit. These include:

i) Reduce additional anthropogenic pressures – management strategies aimed at relieving additional pressures such as overfishing and degraded water quality may improve resilience to climate change impacts. Some anthropogenic impacts may mitigate climate change effects (for example, increased turbidity due to sediment runoff may reduce the potential impacts of elevated ultraviolet exposure), and these interactions should be fully investigated.

ii) Intervention to protect critical geomorphological features – critical habitats may be protected or managed actively. For example, important nesting beaches may be artificially renourished, or groynes may be used to influence hydrodynamics to either reduce erosion or direct deposition. A variety of engineering options, both 'hard' and 'soft' are available to treat coastal issues in other environments, and these may be evaluated for critical management locations.

iii) Continued research to address knowledge gaps, more effectively predict future changes, and to assess their geomorphological, ecological and other significance. This is essential if scant resources are to be effectively assigned to systematically prioritised issues where enduring satisfactory outcomes can be achieved.

### 21.6.3 Future research

Knowledge gaps remain which limit capacity to predict the response of major geomorphological features to climate change. Conceptual models exist that link critical ecological, physical and geomorphological factors and processes, but these linkages have rarely been quantified and many of the basics remain unclear. Major knowledge gaps and priority areas for future geomorphological research include:

- Sediment budgets and links to landforms and processes in contemporary settings are poorly constrained, hindering modelling of future responses. This is true for environments reliant on biogenic and siliciclastic sediments.
- Palaeohistories are incompletely known, with relatively poor geographic and temporal coverage. High priority investigations to inform predictions of possible future responses include: i) establishing accurate palaeohistories of storm occurrence from a wider area of the GBR, ii) more and more detailed reconstructions of previous geomorphological response to sea level change, and different storm, hydrodynamic and climate regimes, and iii) more widespread and detailed histories of island accretion and dynamics.

- Bathymetric and topographic control is poor for many parts of the GBR. The paucity of high quality topographic data and geomorphological mapping means that valuable baseline information is commonly not available. Where it does exist, basic spatial data is often inadequate for sophisticated numerical modelling of geomorphic change under various climate change scenarios.
- The morphodynamic behaviour of many geomorphological features is poorly understood, particularly with respect to the quantification of natural variability, sensitivity to different physical, biological and chemical forcing functions, and thus potential thresholds for change. Understanding the nature of thresholds at which geomorphological features in the GBR will switch from accretion to erosion, or will have modified stability, is critical to their effective management. The significance of spatial variations in geomorphological sensitivity and vulnerability to the effective management of critical organisms dependent on geomorphological services should be systematically addressed.
- Identification of most appropriate sites for conservation management based on geomorphological history and growth trajectories (ie reefs at juvenile and mature stages with greatest structural complexity and habitat diversity), and most geomorphologically resilient to predicted climate change impacts.

A critical issue related to the preceding point is whether the intrinsic variability observed for most geomorphological features will remain and continue to satisfy ecosystem demands that can no longer be serviced on modified features. For example, if rising sea levels erode beaches and expose beach rock that is unsuitable for turtle nesting on some cays, will enough sandy cays or beaches remain to accommodate this displaced nesting effort? Although particular changes will be catastrophic for certain organisms, some geomorphological features and organisms will also undoubtedly benefit. Resolution of this issue, with an understanding of spatial and temporal variations these responses, is critical if limited management resources are to be effectively directed.

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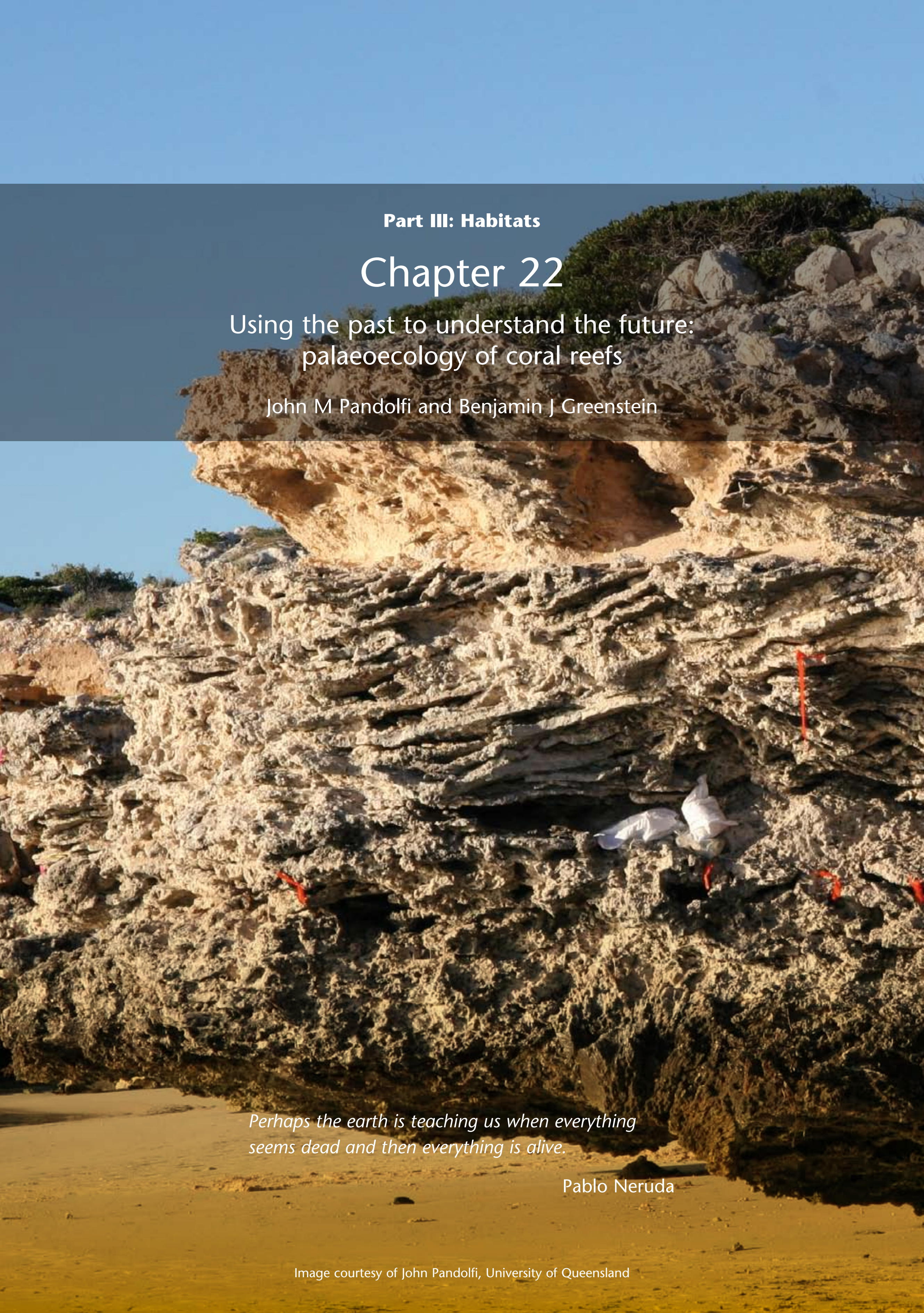


## Part III: Habitats

# Chapter 22

# Using the past to understand the future: palaeoecology of coral reefs

John M Pandolfi and Benjamin J Greenstein

*Perhaps the earth is teaching us when everything seems dead and then everything is alive.*

Pablo Neruda

Image courtesy of John Pandolfi, University of Queensland

## 22.1 Introduction

Present anthropogenically-induced climate change is now well substantiated[91]. The effects of climate change on the marine biosphere are the subject of great concern[64,133,63] but we simply do not have enough long-term ecological data to predict potential changes in the geographic distribution and composition of marine communities. Hence, long-term time-series data on the past response of marine ecosystems to climate change have become increasingly relevant. Coral reefs provide a legacy of their existence because they accumulate vast thicknesses of biogenic sediments, so it is possible to acquire time-series ecological data in the form of variations in reef coral community structure during past episodes of environmental change. It is perhaps fortuitous that many of the proxies that we use to understand past climate on earth can be found in the major architectural components of reefs, the scleractinian corals. However, most emphasis has been placed on using corals as ancient thermometers and much less on their ecological response to global climate change.

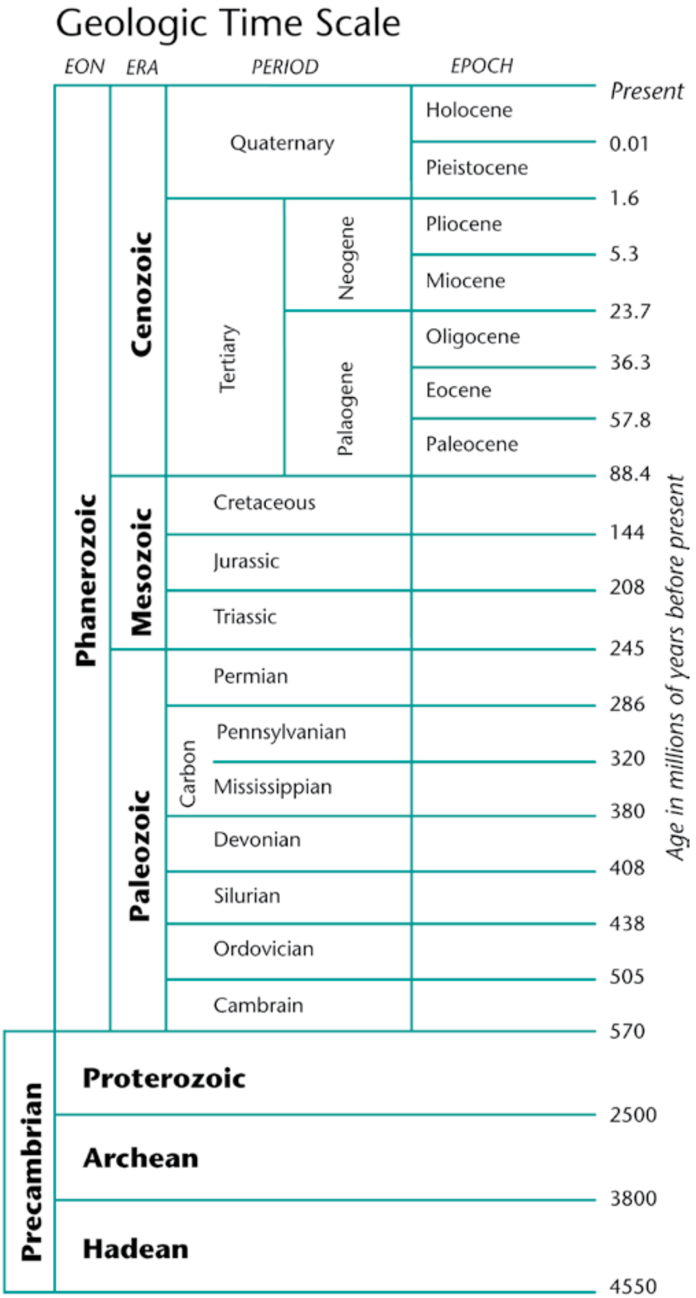
### 22.1.1 Defining history

There have been many attempts to place the present and projected global climate change into an historical context (eg Crowley[32]). However, most of these attempts are undertaken by palaeoclimatologists interested in the comparisons of rates and magnitudes of physical change, but not the corresponding rates and magnitudes of ecological change. In this contribution we take a close look at the major climatic variables most likely to change in the coming century by tracing their history throughout various intervals of geological time. We conveniently divide these intervals into 'deep time' and the Quaternary (Pleistocene and Holocene; see Figure 22.1) so that lessons can be learned from multiple time scales. After we discuss these physical changes, we summarise the biological response of tropical marine ecosystems, with special attention to coral reefs. We then present a series of examples of the response of coral reefs to past global climate change and use these results to provide guidance as to likely scenarios for the future of the Great Barrier Reef (GBR) under predicted climate change.

This contribution covers a large range of spatial and temporal scales. Throughout, it is critically important to consider the scale-dependence of our discussion. The derivation of principles and analogies from geological timescales and perspectives is often not directly applicable to studies and events occurring at ecological timescales. For example, current concern over the future of the GBR is placed in the context of upcoming decades or centuries. The geological record can be used to examine responses of reef ecosystems to both prolonged and rapid perturbations in the past. However, the resolution to determine how reefs 'looked' during intervals (decades to centuries) over which rapid perturbations occurred is only sporadically encountered (eg Pandolfi et al.[102]).

On the other hand, the unfolding of natural ecological processes often occurs over time spans that are far greater than those directly observable by living scientists. This may leave critical challenges to managers of marine ecosystems over the short time scales inherent in human generations, or even shorter political cycles. The geological record of coral reefs is the exclusive (and hence, indispensable) source of data that can inform managers about processes operating over longer time intervals. In this chapter we attempt to summarise the relationship between past climate and the ecological history of reefs. We find that, in the absence of human impacts, reefs either persisted in the face of natural changes in climate throughout their long geological history, despite large environmental variability, or that any deleterious ecological effects were superseded by replenished ecosystems.

***Figure 22.1*** *Geological time scale[a] showing the age of the Phanerozoic (deep time) and the Quaternary*



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[a] US Geological Survey: http://www2.nature.nps.gov/geology/usgsnps/gtime/gtime1.html

## 22.2 Vulnerability of coral reefs to climate change

### 22.2.1 Exposure

### *22.2.1.1 Phanerozoic rates and magnitudes of environmental change*

Physical controls on reef building and decline, over geologic timescales, include variations in seawater chemistry and cyclic changes (at varying time scales) in sea level, sea surface temperature and global levels of atmospheric $CO_2$. These factors are necessarily interrelated. In the following sections, we outline the nature and distribution of these factors over the last 540 million years – the Phanerozoic Eon of geologic time (Figure 22.1).

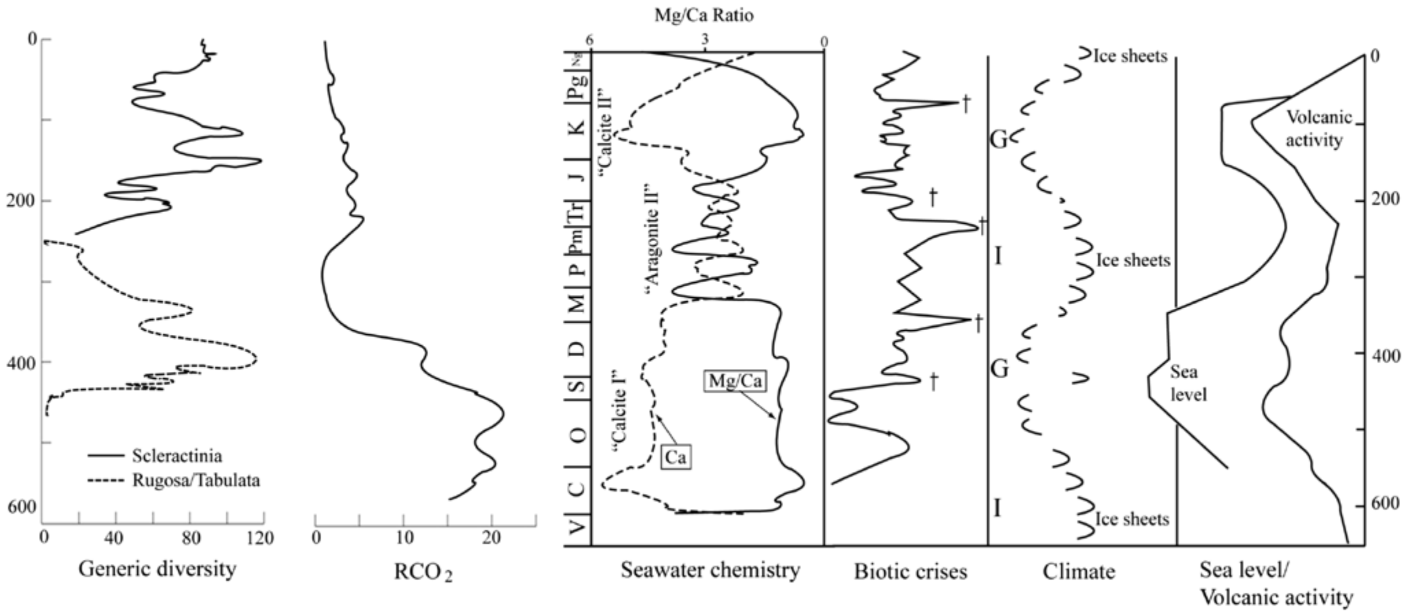
**Seawater chemistry**

The mineralogy of inorganically precipitated calcium carbonate varied between calcite and aragonite over geologic time[114], calcite is the more stable of the two and has typically been better preserved. The Phanerozoic Eon can be divided into three intervals of 'aragonite seas' and two intervals of 'calcite seas' based on which mineral phase was predominant (Figure 22.2). 'Aragonite I,' 'Calcite I' and a portion of 'Aragonite II' are encompassed by Palaeozoic time (an interval of approximately 300 million years). 'Calcite II' occurs from Jurassic–Oligocene time (170 million years), followed by 'Aragonite III' which began approximately 30 million years ago and continues today. Wilkinson and Algeo[139] and Hardie[56] suggested that each of these intervals is related to secular (extremely long-term) shifts in the magnesium/calcium (Mg/Ca) ratio of sea water imparted by changes in spreading rates along mid-ocean ridges. Stanley and Hardie[125] expanded this work by relating secular oscillations in the carbonate mineralogy of carbonate-secreting taxa to the intervals of calcite or aragonite precipitation described by Sandberg[114]. Their work was, in turn, corroborated by Dickson[34] who used the mole percent of Mg-rich calcite in skeletal elements of fossil echinoderms as proxy for Mg/Ca ratios in sea water during Aragonite I, II and Calcite I, II.

Values for surface ocean pH and alkalinity have been established for the last 60 million years[103,104] (Figure 22.3). From a low value of 7.4 at the beginning of Paleogene time (Greenhouse II), sea surface pH increased to a Miocene high of 8.3 before declining to its current level of 8.1 (note no data are available for the Late Eocene and Oligocene epochs). In the context of this time scale, the fact that sea surface pH declined from 8.2 to 8.1 in only the last 40 years is particularly sobering.

Today there is much concern over the degree to which ocean acidification associated with increased carbon dioxide ($CO_2$) will negatively impact biomineralisation in the sea[38]. The fossil record is equivocal on this issue. For example, Palaeozoic reefs were dominated by calcitic corals so this part of the geological record is mute on the topic of the effects of ocean acidification on modern aragonitic corals. Late Cretaceous reefs were dominated by aragonitic corals until Mg/Ca ratios got low enough to favour the rudistid bivalves. The 'Palaeocene lag' in the recovery of reef ecosystems from the end-Cretaceous extinction is attributed to 'calcite sea' geochemistry[125]. However, pH was lower in the Palaeocene as well (Figure 22.3). Following the Palaeocene, coral reefs diversified as ocean pH increased and atmospheric $CO_2$ decreased – see discussions below.

***Figure 22.2*** *Secular trends in a variety of physical, chemical and biological attributes of the Earth system over the last 600 million years, Y-axis at same scale for all plots. From left to right: generic diversity of reef building corals*[b]*; atmospheric $CO_2$ expressed as number of times higher than approximate present value of 300 parts per million by volume ($RCO_2$*[18]*); timing of flux in Mg/Ca concentration of seawater producing aragonite or calcite seas*[125]*; global marine diversity (five largest mass extinctions indicated with crosses); timing of ice sheet advance/retreat during icehouse and greenhouse phases; global sea level, history of volcanic activity (biotic crises, climate, sea level and volcanic activity modified from Fischer*[41]*)*



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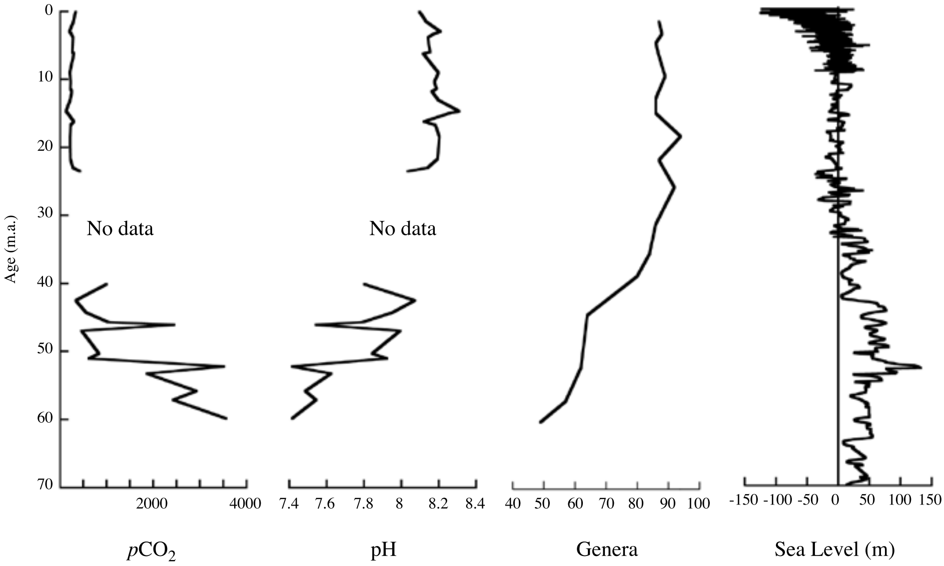
b Paleobiology Datebase (2006) The data were downloaded from the Paleobiology Database on 24 May, 2006, using the group name 'marine invertebrate' and the following parameters: time intervals = Gradstein 7: Stages, region = Global, paleoenvironment = marine, order = Tabulata, Rugosa, Scleractinia

***Figure 22.3*** *Secular variation of physical, chemical and biological attributes of the Earth system over the last 60 million years; $pCO_2$ and pH values from Pearson and Palmer[104]; generic diversity of scleractinia from the Paleobiology Database[c]; sea level data from Miller et al.[84]*



## Sea level, sea surface temperature and global $CO_2$ levels

Fischer[40,41] outlined a nested set of climate cycles apparent over the last 700 million years. These cycles, operating on timescales of $10^8$, $10^7$ and $10^4/10^5$ years, were correlated with biotic crises observed in the fossil record of marine invertebrates. The longest cycle (defined by Fischer[40] to occur between 'Icehouse' and 'Greenhouse' intervals) was interpreted to be the result of changes in $pCO_2$ caused by variation in the Earth's mantle convection strength (and resulting sea-floor spreading rates). These refer to periods in which icesheets dominated the poles – the Icehouse, which we are currently in – and times when the poles were free from ice – the Greenhouse. These terms are not to be confused with glacial and interglacial periods, which can occur within these cycles. Greenhouse intervals occurred during the early-mid Palaeozoic and between Jurassic-Palaeogene time (Figure 22.2). They were characterised by high sea level (amplitudes are the subject of some controversy – recent work, eg Miller et al.[84], suggests that sea level in the Cretaceous was 100 ± 50 metres higher than today), rapid sea-floor spreading rates, elevated atmospheric $CO_2$ concentrations and elevated sea surface temperatures (5 to 9°C above present during Greenhouse II[147,116]). In contrast, the Icehouse intervals bracketing the warmer periods were times of lower sea level, continental glaciation, lower concentrations of atmospheric $CO_2$ and lower temperatures (atmospheric temperatures 8 to 10°C below present during the glacial episodes of the present icehouse phase[106]). Sea level variations accompanying transitions

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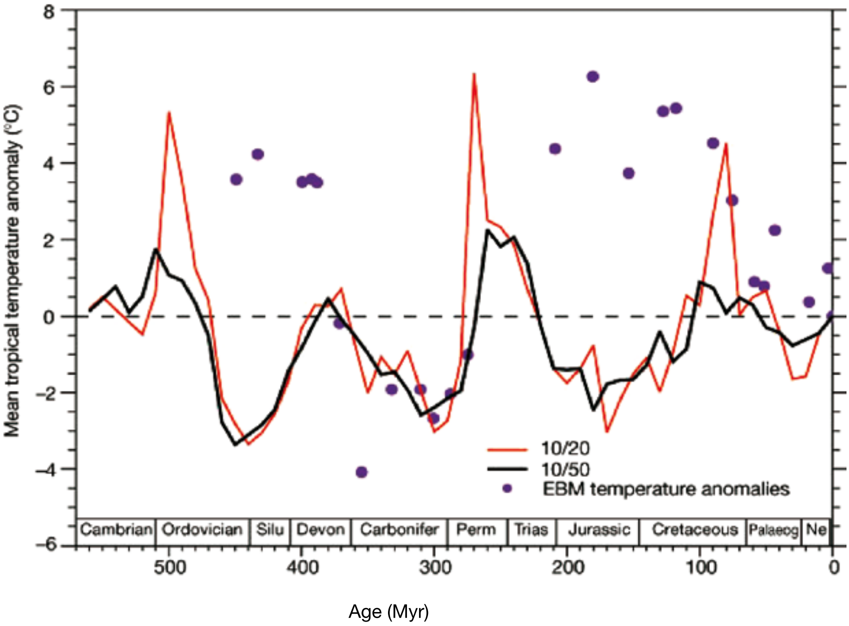
[c] Paleobiology Datebase (2006) The data were downloaded from the Paleobiology Database on 24 May, 2006, using the group name 'marine invertebrate' and the following parameters: time intervals = Gradstein 7: Stages, region = Global, paleoenvironment = marine, order = Tabulata, Rugosa, Scleractinia

from Icehouse to Greenhouse intervals were up to 200 metres[84]. Temperature fluctuations (examined as 10 million year or longer averages) in the tropics occurred at far greater magnitudes than have been observed today or projected into the future[131,120] (Figure 22.4).

In a series of papers, Berner and colleagues[16,17,18,20,19] quantified global atmospheric $CO_2$ levels over essentially the same time interval described above. Their model allowed only for long-term (again, 10 million year or longer averages) and hence short-term fluctuations were not delineated. Their results corroborated Fischer's[40,41] earlier work. Very high levels (25 times that of today) of $CO_2$ were present during early Palaeozoic time (approximately 440 million years ago, during 'Calcite I', as defined above; Figure 22.2) followed by a large drop (ironically, to approximately modern levels: 306 parts per million by volume[18]) at 360 million years ago, near the end of Devonian time, most likely catalysed by the rise of vascular plants and their spread throughout terrestrial ecosystems[2,111,35]. The resultant accelerated uptake of $CO_2$ by weathering of silicate rock as plants with deep root systems evolved was complemented by enhanced burial (and hence trapping of $CO_2$) of organic material in sediments. By 325 million years ago, the reduction of $CO_2$ was sufficient to plunge the earth into Icehouse II, which lasted 145 million years, into mid-Jurassic time. Greenhouse II persisted for approximately 150 million years, during its zenith in Late Cretaceous time (80 million years ago ), $CO_2$ levels were five to six times higher than today[18,103]. Beginning 33.5 million years ago, in Early Oligocene time, the earth began to enter the icehouse state (Icehouse III) that continues today.

***Figure 22.4*** *Tropical sea surface temperature curve throughout the Phanerozoic derived from isotopic analyses (lines) and tropical surface palaeotemperature anomalies calculated by an energy-balance climate model (filled circles). 10/20 and 10/50 indicate running means at various temporal resolutions (eg 10/20 means step 10 million years, window 20 million year averaging) from Veizer et al.*[131]



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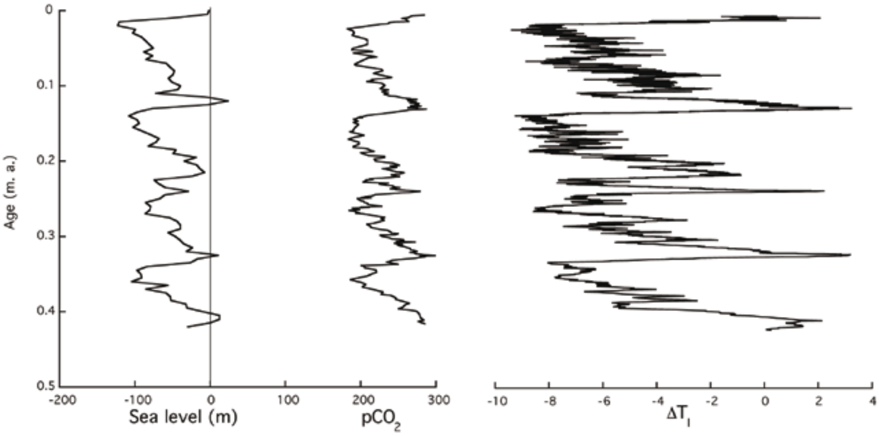
### 22.2.1.2 Quaternary rates and magnitudes of climate change

#### Milankovitch cycles

High-resolution climate proxies for the Quaternary, particularly the last 800,000 years, are derived primarily from deep-sea sediments and ice cores. These proxies indicate that, as the earth entered a full glacial period (a continuation of Icehouse III), growth and decay of ice sheets in the northern hemisphere were controlled by $10^4$- to $10^5$-year scale climate changes forced by natural cyclic changes in several parameters of Earth's orbit (so-called Milankovitch cycles[d][84]). Global sea levels underwent at least 17 cycles of rise and fall during the last 500,000 years[27], with amplitudes of greater than 100 metres characterising glacial and interglacial stages. Average rates of sea level change between glacial and interglacial intervals approached 50 centimetres per century[84].

Variation in atmospheric $CO_2$ and global temperature in response to the waxing and waning of ice sheets also are recorded by climate proxies. Famously, the Vostok ice core spans greater than 400,000 years and records the atmospheric response to four complete glacial-interglacial cycles (Figure 22.5). At the onset of each warm interval, $CO_2$ increased by 8 to 10 parts per million by volume per thousand years, coincident with temperature increases of between 0.5 to 1.0°C per thousand years[106]. During the latter half of this interval, rapid and dramatic changes in sea surface temperature have been calculated for the Western Mediterranean over the last 250,000 years, where rates of sea surface temperature increase have apparently exceeded 1.5°C per century[83]. This record has now been extended, first with reports from the European Project for Ice Coring in Antarctica (EPICA) group of cycles back to 650 thousand years ago from a new ice core in Antarctica[122], and then to 800,000 still showing Milankovitch cycles with temperature and $CO_2$ in lock step variation through the entire interval[145].

**Figure 22.5** *Climate and sea level fluctuations over Late Quaternary time. Sea level data from Miller et al.[84], $CO_2$ and temperature data from Petit et al.[106], temperature ($\Delta T_I$) expressed as changes from the present temperature at the inversion (atmospheric) level*



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[d] The cycles influence the amount of sun energy received by earth. They include obliquity (changes in the angle of earth's axis of rotation with respect to the sun); eccentricity (changes in the circularity of Earth's orbit around the sun); and precession of the equinoxes (changes in the position of the Earth in its orbit around the sun at the time of the equinox). The cycles are 41,000, 100,000, and 23,000 years, respectively.

### Sub-orbital and abrupt climate change

Evidence from the last interglacial (approximately 128 to 118 thousand years ago) indicates substantial changes in sea level also occurred over much shorter intervals than could be produced by Milankovitch style forcing. For example, field evidence initially published for the Bahamas, indicates two episodes of reef building separated by a surface that clearly was exposed to the atmosphere. Dates obtained from corals preserved on either side of the exposure surface indicate that the fall and subsequent rise in sea level that produced the reef sequences occurred in as little as 1500 years and suggests rates of sea level change approaching 70 centimetres per century[30,143]. Results of additional work in the Seychelles, Maldives and Western Australia[54,137,138] suggests this also was a global sea level event.

A significant amount of new information has been gathered over the past several years that point to a large number of 'abrupt climate change' events during the more recent geologic past when most living marine communities originated and thrived. Abrupt climate change occurs when 'the climate system is forced to cross some threshold, triggering a transition to a new state at a rate determined by the climate system itself and faster than the cause'[88]. Recent palaeoclimatic studies indicate that regional temperature fluctuations of as much as 8 to 16°C occurred repeatedly in as little as a decade or less over the past 100 thousand years[127,119]. One of the best known and studied of these events is called the 'Younger Dryas' event, so called because a cold-loving plant species' pollen (*Dryas octopetala*, an arctic-alpine herb) reappeared during this interval. It had an abrupt beginning 12,800 years ago and an even more abrupt end 11,600 years ago. The intervening interval was characterised by cooler than normal temperatures, but the transition out of the cooling period resulted in a warming episode of 8°C in a decade.

During the last 10,000 years (Holocene time), rapid changes in climate, also on the scale of between 8 to 16ºC, occurred repeatedly on decadal time scales[119,4]. These changes were apparently forced by cyclic (1500-year) changes in solar activity/brightness[21] and to date have been preserved by climate proxies in the northern hemisphere (eg Andresen et al.[6] and Hu et al.[61]). Recently Mueller et al.[86] suggested that similar cycles of solar activity also operated during the last interglacial, 128 to 118 thousand years ago.

The best known of these types of short-term climatic cycles are the Dansgaard–Oeschger events and Heinrich events. Dansgaard–Oeschger events are a period of slow cooling followed by one of rapid warming. They have been detected by rapid shifts in isotopic composition in ice cores. Methane, regarded as an index of tropical wetland vegetation, also co-varies with the isotopic shifts. Heinrich events appear to be correlated with Dansgaard–Oeschger events and are characterised by the rapid break-up of northern hemisphere ice sheets that expand to a critical size, then break up along their oceanic margins. These events act as a switch to turn the Atlantic conveyor on and off, causing rapid climate changes in the north Atlantic region on the order of 5 to 10°C in a decade or less.

### *22.2.1.3 Summary*

The long-term pattern of climate change preserved in the geologic record indicates substantial departures from that of human experience, especially magnitudes of temperature and $CO_2$ during deeper intervals of geological time. For example, temperature was up to 6°C higher in tropical Phanerozoic ecosystems than present day (Figure 22.4), similarly, $CO_2$ levels were up to 20 times higher. Therefore, the *magnitude* of projected climate change is within the past history of metazoan, and even reef life, but the *rate of change* is unknown. This is due to the fact that the patterns in deeper time are not resolvable to scales relevant for present day changes because they are binned by 10 million year intervals, thus we don't yet know what the rate of change has been in deeper time when magnitudes exceeded present day and projected values.

Perhaps more relevant for modern managers are more recent patterns in temperature and $CO_2$ observed during the Quaternary, where both magnitudes and rates of change can be observed. Here we see that the magnitude and rate of temperature change are both greater in the Quaternary than projected for the next century by the Intergovernmental Panel on Climate Change (IPCC) (Table 22.1). Importantly, the highest rates of temperature increase during sub-orbital abrupt climate change events have not elevated Quaternary temperatures beyond those seen today. Projected temperature increases over the next century could elevate temperature near highest levels observed for the Quaternary. However, the rate of change in temperature will still be below the highest rates of change seen in the atmosphere during the initiation of each interglacial period within the last 400,000 years[106]. In contrast, present day and projected magnitudes and rates of $CO_2$ rise now far exceed Quaternary levels (Table 22.1).

***Table 22.1*** *Comparison of rates of change in temperature, $CO_2$ and sea level estimated for various intervals in the geologic past and those predicted for the next century. Where: kyr represents thousands of years, ppmv is parts per million by volume and m/century is metres per century*

| Geologic Interval | Age (kyr) | Temperature (°C/century) | $CO_2$ (ppmv/ century) | Sea level (m/century) | Reference |
|---|---|---|---|---|---|
| Pleistocene-Holocene | 11.60 to 10.10 | 1.0 | 2.0 | 0.8 | Severinghaus et al.[119], Stocker[127], Miller et al.[84] |
| Pleistocene-Holocene | 11.64 to 11.63 | 50 to 100* | N/A | N/A | Severinghaus et al.[119] |
| Quaternary | 156.35 to 129.70 | 0.042 | 0.34 | 0.52 | Petit et al.[106], Miller et al.[84] |
| Quaternary | 333.60 to 322.16 | 0.12 | 3.4 | 0.56 | Petit et al.[106], Miller et al.[84] |
| Palaeocene-Eocene | 55,000 to 54,925 | 0.007 | 0.2 | 0.06 | Zachos et al.[147], Miller et al.[84] |
| Next Century | N/A | 1.2 to 5.8 | 111 to 732 | 0.07 to 0.86 | IPCC[64] |

* Represents estimate for a 'decadal step' associated with the end of the Younger Dryas Interval

## 22.2.2 Sensitivity

### 22.2.2.1 Phanerozoic reef response

Reef systems have a geologic history extending back 2.5 thousand million years or 2.5 Ga. Then, microbial stromatolites built wave-resistant structures soon after tectonic processes produced widespread shallow marine shelf environments[89]. Reef systems comprising corals extend to at least 450 million years ago[58] and most likely earlier[115]. Over geological timescales since that time, reef coral communities have been durable in the face of global biotic crises, reappearing after each of the 'big five' mass extinction events[110] and numerous smaller mass extinction events. However, recovery intervals ranged from four million years (following the end-Triassic event[132,136] to over 100 million years (following the collapse of the mid-Palaeozoic reef ecosystems beginning near the end of Devonian time[89]). Although reef crises are correlated with mass extinction events, Flügel and Kiessling[44] have demonstrated that the magnitude of mass extinctions and reef crises (the former measured as declines in biodiversity, the latter as declines in carbonate production) are rarely equivalent, suggesting that they are not always causally related.

Early to mid-Palaeozoic coral reef ecosystems fall into 'Calcite I' of Sandberg[114], and are dominated by calcitic rugose, tabulate and heliolitid corals (as well as calcitic stromatoporoid sponges). The collapse of the Devonian coral reef ecosystem resulted in a loss of framework-building taxa and was followed by a transition to 'Aragonite II' in mid-Mississippian time[114]. Although coral components of reef ecosystems are unimportant during the latter half of the Palaeozoic, algae secreting high-magnesium calcite skeletons and aragonitic phylloid algae became dominant constituents of late-Palaeozoic reef ecosystems[146,43].

'Aragonite II' persisted through the Permo–Triassic extinction event; when reef building resumed in mid-Triassic time, a community of high-magnesium and aragonitic organisms (notably sponges and red algae) were responsible[45,118]. Scleractinian or 'stony' corals, which build aragonite skeletons, join these communities in Late Triassic time[126,15] and, following the end-Triassic extinction, dominate global reef systems until the mid-Cretaceous shift from aragonite to calcite seas[124,76]. By Late Cretaceous time, calcitic rudistid bivalves began to supplant scleractinian corals as dominant reef builders[117,69]. Stanley and Hardie[125] suggest that the replacement of scleractinians by rudists was a consequence of the decline of aragonitic corals resulting from a pronounced decrease in the magnesium/calcium ratio of sea water by Late Cretaceous time.

The timing of recovery of the coral reef ecosystem from the terminal Cretaceous extinction event is the subject of some controversy. Many researchers have suggested that reefs did not attain Cretaceous levels of geographic extent and complexity until Oligocene-Miocene time: the beginning of 'Aragonite III' (Figure 22.2) (eg Frost[48], James[68], Sheehan[121], Fagerstrom[37], Bryan[24], Hallock[55], Stanley and Hardie[125]). More recently however, Baceta et al.[8] suggest that this impression may largely be the result of preservation bias, and present an analysis of an extensive early Palaeogene section to demonstrate a rapid (two million years) recovery of coral-dominated reef systems. Moreover, Kiessling and Baron-Szabo[73] show that extinction rates of scleractinian corals across the Cretaceous/Palaeogene boundary were only moderate in comparison with other invertebrates.

What is clear is that luxuriant and widespread reef growth is observed during the Oligocene Epoch of the Palaeogene Period[47,48], even after global climates had cooled substantially[144]. This interval coincides with the onset of 'Aragonite III' and the establishment of Mg/Ca ratios sufficiently high to allow aragonitic reefs to flourish once again.

Reefs tend to disappear significantly earlier than other taxa at terminal extinction events. For example, Cretaceous reefs vanished 0.7 to 1.5 million years before the end-Cretaceous extinction[70]. This general pattern holds also for the reduction and collapse of early and middle Palaeozoic reefs, which generally occurred 0.5 to 1.0 million years earlier than the accepted extinction boundaries for Early Cambrian, Late Ordovician and Late Devonian events[31]. This suggests that, regardless of the cause of extinction, reef ecosystems might be more sensitive indicators of environmental perturbation than are other taxa.

Kiessling[71] presented a synthesis of the palaeolatitudinal distribution of 2910 Phanerozoic (pre-Quaternary) reef (corals and other important calcified constituents) sites compiled from the literature and compared it to a variety of palaeoclimatic curves that included temperature and atmospheric $CO_2$[46,16,131]. Neither the total latitudinal range of reefs nor the width of the tropical reef zone was significantly correlated with palaeoclimate inferred from the subsidiary data[71]. Relevant for living coral reefs, Kiessling[71] observed that fluctuations in the width of the tropical reef zone were in phase with climatic variations only during Cenozoic time.

The influence of seawater chemistry on skeletal mineralogy appears to be particularly strong for morphologically simple taxa that exert relatively weak control over their own calcification – including reef-building corals. Hence, the Mg/Ca ratio and saturation state of carbonate in sea water have been first-order controls over the success of individual reef-building taxa, resulting in a remarkable correspondence between their mineralogy and that of inorganic carbonates over geologic time. Ries et al.[112] provide experimental evidence that changes in seawater chemistry may result in the precipitation of biogenic calcite in scleractinian corals that exclusively precipitate aragonite skeletons. Modern corals grown in aquaria full of 'Cretaceous' seawater with reduced Mg/Ca ratios compared with present day also grew more slowly. Ries et al.[112] relate the mid-Cretaceous decline and Oligocene resurgence of corals as reef builders to the variation in seawater Mg/Ca ratios. Future experimental work on changing seawater chemistry and its effects on coral growth over longer time intervals will be a welcome addition to understanding the effects of climate change and ocean acidification on coral reefs. Fine and Tchernov[39] showed that scleractinian corals grown in experimental acidified conditions lost their skeletons, but were able to sustain basic life functions, including reproductive ability, in a sea anemone-like form. They resumed skeleton-building when reintroduced to normal marine conditions. They concluded that 'physiological refugia' allow corals to alternate between non-fossilising soft body forms and fossilising skeletal forms in response to changes in ocean chemistry.

In summary, coral-dominated reef systems recovered after past climatic instability imparted as the Earth passed between one stable climatic state and the other. It is clear that the acme of reef development, both in geographic extent and coral diversity (Figure 22.2), occurred during past Greenhouse intervals. Prior to the mid-Palaeozoic (Late Devonian) collapse of the reef system, equatorial reef and inter-reef carbonate platforms covered an estimated 10 times the areal extent witnessed today[31]. In contrast, the rise of the modern reef system beginning in mid-Palaeogene time occurred in tandem with falling levels of atmospheric $CO_2$, increasing Mg/Ca, increasing alkalinity of the world's oceans and global cooling (Figure 22.3). Hence, aragonite-secreting corals, living in a chemical environment that fosters

precipitation of aragonite, build reefs today. This combination of climatic and geochemical factors was not present during intervals in the geological past that witnessed widespread reef development. Therefore, it would be imprudent to cite widespread reef development during past Greenhouse intervals as evidence that the modern reef system will likely benefit from climate change.

### *22.2.2.2 Quaternary reef response*

The Quaternary fossil record of reef coral communities is an ideal database for assessing the vulnerability of the modern reef system to climate change. First, reef coral communities preserved in Quaternary strata are taxonomically congruent with modern reef coral communities[65,92]. Second, Quaternary reef coral communities flourished during an interval of rapid and dramatic climate change for which highly precise climate data are available (Figure 22.5). Third, during the last interglacial, sea level was two to six metres higher[29], with consequent exposure of a two to six metre terrace throughout the tropics that preserves coral reefs. Finally, Quaternary fossil reef communities are remarkably well preserved[50] allowing for a great number of coral taxa to be identified with a degree of certainty that compares closely with modern taxa[95,96,99,97].

Recent studies have examined reef coral community dynamics over geologic time scales (Late Pleistocene and Holocene time) and extended spatial scales (10 to 1000's km) and applied the results to further our understanding of processes affecting the community structure of modern coral reefs (reviewed in Pandolfi[94] and Pandolfi and Jackson[98]). For coral reefs, palaeoecology provides a unique tool for placing perturbations affecting modern reefs into a temporal context that exceeds the scope of traditional ecological studies[93,63,100]. An additional body of recent work has compared the community structure of Pleistocene reef corals to that of modern reef coral communities to assess whether a precedent exists for the ongoing collapse of modern reef systems[7,53] as well as the magnitude[66,67] and mechanism[100] of the collapse. On a global scale, coral species underwent dramatic changes in distribution and abundance during Quaternary glacial-interglacial cycles that caused sea level to repeatedly flood and drain from continental shelves and oceanic islands[108].

The higher resolution provided by the Quaternary (the last 2.6 million years) fossil record of coral reefs provides an opportunity to dissect the broad patterns of response observed over an eon of geologic time. Moreover, modern coral communities are derived largely from species that survived biotic turnover in Plio-Pleistocene time[132,25]. Hence, a review of the response of these communities to the rapid and dramatic fluctuations in temperature, sea level, and atmospheric $CO_2$ that characterise the Late Quaternary is especially appropriate for an assessment of the vulnerability of the modern reef system to climate change.

#### The Great Barrier Reef

The history of the Great Barrier Reef (GBR) spans multiple episodes of global environmental change, yet it is a relatively 'young' geological structure that did not respond to favourable environmental conditions early on. In fact, the central Queensland continental shelf has enjoyed warm tropical waters that could well have supported coral reef growth for the past 15 million years[33]. However, it is now generally recognised that the initiation of the GBR did not occur until approximately 600 thousand years ago, and the GBR reefs as we know them probably didn't occur until around 365 to 452 thousand years ago[134]. This is coincident with Marine Isotope Stage 11, perhaps the warmest interglacial of the past 450 thousand years[60], and one with climatic conditions most similar to those we are now experiencing[77]. Larcombe and Carter[75] believe that the ‘switching-on’ of the GBR was not only related to the ‘mid-Pleistocene transition’ from 41 to 100 thousand year-long climatic cycles[14], but also to the development during Marine Isotope Stage 11 of a marked high stand that enabled sustenance of both a cyclone corridor and a reef tract along a relatively wide and deeper water continental shelf.

Webster and Davies[134] showed remarkable consistency in community composition throughout many intervals of Pleistocene reef development on the GBR at Milankovitch time scales. Recent cores drilled through Ribbon Reef 5 have shown that the GBR has been able to re-establish itself repeatedly despite major environmental fluctuations in sea level, temperature and $CO_2$ over the past several hundred thousand years[134]. Moreover, Webster and Davies[134] showed that the reefs have maintained a similar coral and algal species composition during their repeated formation. Species abundance data were derived from 55 coral species from 20 genera and coralline algal associations were derived from an analysis by Braga and Aguirre[23].

Growth of the GBR’s fringing and nearshore reefs during the past 10 thousand years (the Holocene) has been upon Pleistocene topographic highs[123]. Holocene fringing reef growth on the GBR varies naturally through time and appears to be episodic, responding closely to sea level and climate change[123]. The most significant period of active reef growth occurred between 7500 and 5500 years before present as the post-glacial marine transgression (sea level rise) progressed. Smithers et al.[123] attribute the turn-off of these reefs at the end of this period to the exhaustion of available accommodation space (the water depth of the shallowest growing reef) over suitable substrates, stresses associated with sea level stabilisation and slight fall near the end of this time, and climate changes associated with changes in the intensity and frequency of El Niño-Southern Oscillation conditions. They also noted other periods of moribundity since the mid-Holocene that are related to the filling of accommodation space, reduced flushing since the optimal Holocene high-energy window (7500 to 5500 years before present) and reduced calcification and increased disturbance associated with climate changes. These moribund reefs were characterised by healthy but non reef-building coral communities. The authors note that many living fringing nearshore coral reefs are built upon reef structures that were constructed in the distant past. The main point from these findings is that interruptions in reef growth, even climatically induced, are part and parcel of the Holocene nearshore record, but the living biophysical structure of the coral reef remained in the face of episodic moribundity, much of which can be correlated with climatic changes.

### Indo-Pacific coral reefs

Like the GBR, Indo-Pacific reefs have flourished throughout several Milankovitch cycles during the past several hundred thousand years. For example in Papua New Guinea, vibrant interglacial reefs preserved in uplifted terraces along the northern coastline of the Huon Peninsula preserve fossil reefs over at least the past 340 thousand years[28]. These Pleistocene reef coral assemblages show pronounced constancy in taxonomic composition and species diversity between 125 and 30 thousand years[92]. Differences in reef coral community composition during successive high stands of sea level were greater among sites of the same age than among reefs of different ages, even though global changes in sea level, atmospheric $CO_2$ concentration, tropical benthic habitat area and temperature varied at each high sea level stand[93]. Thus, local environmental variation associated with runoff from

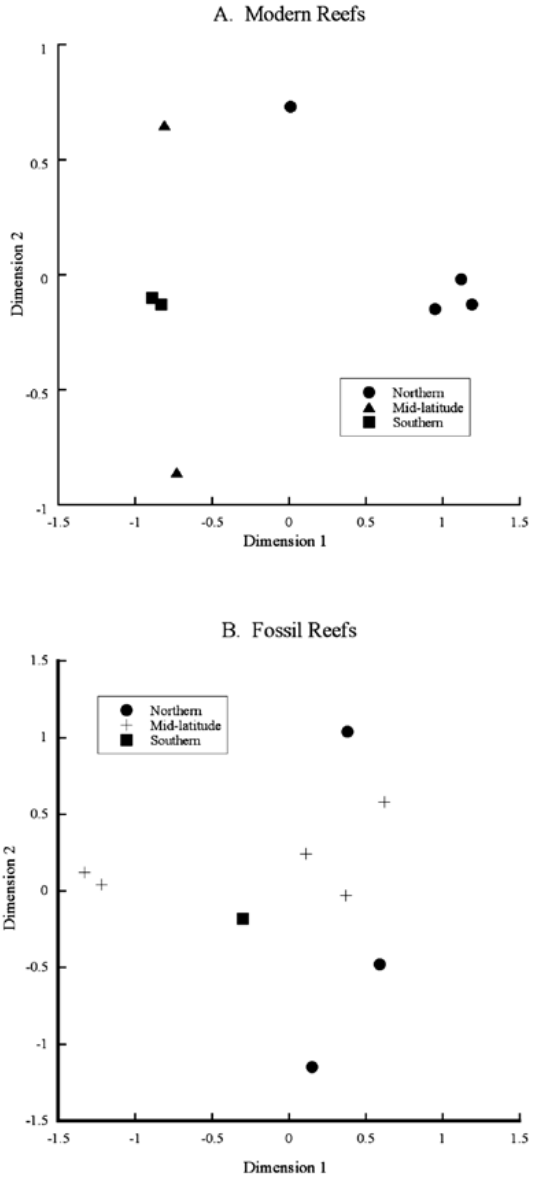
the land had greater influence on reef coral community composition than variation in global climate and sea level. There is also evidence that ecologically equivalent reefs were built successively during subsequent glacial intervals (sea level low stands) in Papua New Guinea[135].

### Western Australia

Present global climate change is resulting in noticeable range expansions of living corals[82,130,109]. Recent work[51,52] in coastal Western Australia has provided preliminary data on how such range movements might affect the long-term ecological dynamics of coral reef habitats. Well-preserved exposures of Late Pleistocene coral reefs are accessible at several localities over a distance of approximately 12 degrees of latitude that today encompasses the boundary between two biogeographic provinces (Figure 22.6). Comparison of reef coral community composition between adjacent modern and fossil reefs along this environmental gradient revealed that coral taxa expanded their latitudinal ranges during Late Pleistocene time compared to today. The two primary consequences of the range expansions were: i) a reduction of the latitudinal gradient in community composition relative to modern reefs (Figure 22.7), and ii) a resultant lower coral diversity within the latitudinal range.

***Figure 22.6*** *Modern and Pleistocene reef localities from Western Australia compared by Greenstein and Pandolfi[51,52]. Modern localities in italics, except for the Houtman-Abrolhos and Rottnest Islands, which expose both modern and fossil reefs. Additional fossil localities include Cape Range, Lake Macleod-Cape Cuvier (L. M. – C. C.) and Port Denison. Province designations after Wilson and Gillett[142]*

***Figure 22.7*** *Results of two-dimensional non-metric multidimensional scaling of Bray-Curtis dissimilarity values calculated from presence-absence data obtained from modern and Pleistocene reef coral assemblages of Western Australia. A) Modern reefs show a clear distinction, along Dimension 1, between the high-diversity northern reefs of Ningaloo and lower diversity southern reefs of Rottnest Island. A significant ($R^2$=0.81; $p < 0.0001$) correlation exists between Dimension 1 and latitude. Stress for the analysis was < 0.001; B) Pleistocene reef assemblages exhibit a significant, though not as strong, ($R^2 = 0.66$; $p < 0.01$) correlation between Dimension 1 and latitude suggesting that the past distinction of reef coral communities between Cape Range and Rottnest Island was apparently less developed than it is today. Stress for the analysis was 0.09*



A major implication of the patterns observed in Western Australia for the GBR is that increased range shifts of modern corals in response to climate change in the near future could potentially lower regional coral diversity in a similar fashion. The role of biodiversity in enhancing ecological stability has been demonstrated on small spatial and temporal scales[79,87,81]. For coral reefs, the diversity-stability relationship apparently scales up to regional spatial scales[12] and geologic time scales[72]. Hence, mitigation of current threats to coral reef diversity and function becomes especially critical.

### The last glacial maximum

The last glacial maximum, dated to about 18 thousand years ago was a time when sea levels dropped to approximately 120 metres below present day levels. Kleypas[74] estimated the amount of area available during such a drop in sea level for the Caribbean Sea and compared it to modern potential sites for reef growth. She found a greater than 90 percent drop in areas for potential reef growth during the last glacial maximum as compared with the present high sea level stand. Yet coral reef growth since then has been shown to accrete at some of the highest rates observed in coral reef settings. This is shown in the record of reef development from both Barbados and the Huon Peninsula[29]. This interval of reef growth appears not to have been unduly affected by initial starting conditions under which the areal extent of suitable habitat was an order of magnitude less than present.

### Response to sub-orbital climate events

Perhaps the best-known sub-orbital climate event is the Younger Dryas event occurring 11 to 10 thousand years ago. In cores from both Barbados and Huon Peninsula, and in raised reef terraces from Huon Peninsula (Pandolfi unpublished data), rates of coral reef growth during the event itself were indistinguishable from growth before and after the event. This does not mean that reef growth was unaffected by the event since short-term interruptions in reef growth may be difficult to identify in ancient reef deposits. However, the Holocene raised reef terrace from Huon Peninsula, Papua New Guinea, preserves mass mortality events of reef corals mainly from volcanic episodes[102] and the resolution of these intervals is approximately 200 years.

## 22.2.3 Adaptive capacity

Many marine species exhibit a genetic legacy of latitudinal range shifts, local extinctions and expansions, and the marked population fluctuations caused by past climatic variation[57]. Based on this past history, can we expect that regional and global-scale disruption to coral reefs generally, and to the GBR in particular, due to climate change will accelerate markedly in coming decades? Already, relative abundances of corals and of other organisms are changing rapidly in response to the filtering effect of differential mortality (from bleaching and other, more local, human impacts), and differences in rates of recovery of species from recurrent mortality events[9,78,62,90]. Furthermore, many, mainly terrestrial, organisms are already showing signs of evolutionary change in response to climate-induced environmental variation[22]. The degree to which this will hold in coral reefs is subject to intense debate, but the near and distant geological record preserves clear evidence that coral reefs have re-established after previous events. This indicates their ability to either adapt to changes, or exploit refugia in less affected areas, so that when optimal conditions returned, they again spread throughout their range.

Our results from Western Australia indicate that reef corals are able to expand their latitudinal ranges in response to climate change. Work by Pandolfi[92] indicates that refugia also have played a role in the re-establishment of reefs during intervals of climate change during the last 100 thousand years. Refugia likely were important to the survival of molluscan faunas during this same interval[128,129].

### 22.2.4 Vulnerability and thresholds

The vulnerability of the GBR to projected global climate change cannot be considered without an understanding of both the history of reef development and the history of impacts that have led to habitat degradation. The diversity, frequency and scale of human impacts on coral reefs are increasing to the extent that reefs are threatened globally[141]. Until recently, the direct and indirect effects of overfishing and pollution from agriculture and land development have been the major drivers of massive and accelerating decreases in abundance of coral reef species[85,67,1,49,63,100]. These human impacts and the increased fragmentation of coral reef habitat are unprecedented and have the possibility to undermine reef resilience[13], raising the likelihood that modern coral reefs might be much more susceptible to current and future climate-change than is suggested by their geologic history[63,13].

Recent work has sought to understand human impacts by developing time-series data archives that can be used to evaluate trends in the global decline of coral reefs since the arrival of humans. The approach has been to use a number of different kinds of data during several periods to examine the recent past history and present condition of coral reefs to provide a natural baseline for community ecology and coral growth rates. Archaeological sites provide insight into the relationship between the development of civilisation and its evolving impact on coastal marine resources. Historical records such as those found in ships logs, and publications of early naturalists and European colonialists provide a moving window of the natural history and inferred ecology of many coral reef inhabitants. Fisheries records and modern ecological surveys can be used in association with remote sensing data (going back the last 20 or 30 years) to provide a detailed picture of changing environments and biodiversity as human population and consumption, as well as economic globalisation, have accelerated during the past several decades. To document changing physical environments, coring of reef corals provides a proxy for sea surface temperature, rainfall, and river discharge[80] from the geological past to the present. Taken together, these databases provide a holistic view of changing environments and ecology on coral reefs that includes the onset of human disturbances and against which the acquisition of present day data can be evaluated.

Recent findings from sites distributed throughout the tropical world point to the immense importance of understanding historical events when attempting to tease out factors that have or may influence present coral reef biodiversity[100]. At 14 sites worldwide (including the outer and inner GBR and Torres Straits) there was no increase in the acceleration of reef megafauna decline during the past century when disease and climate change appear to have intensified, rather, early and effective overfishing appears to have been the major culprit in reef decline[100]. A recent paper explored the policy implications of the historical ecological work and urged US government officials to adopt the large percentage of no-take areas for their reefs as Australia has done[101]. The main conclusions from the work were: i) overfishing is by far the earliest and most influential human impact on coral reef ecosystems, ii) degradation of coral reefs proceeded from the earliest human interactions and was independent of population growth, and iii) if the trajectories of change on coral reefs are not reversed

the current rate of decline in reef ecosystems will result in their extirpation independent of what happens to Earth's climate. Correlation of reef decline with specific human and environmental impacts over time provides an insight into the processes that are most important in local reef settings. When these processes are uncovered, specific steps can be taken to ameliorate or reverse the decline.

### 22.2.5 Threats to resilience

The magnitude and frequency of documented incidences of abrupt climate change during the recent past history of living coral reefs (less than one million years) has been substantial, yet nowhere have the effects of this change been rigorously studied. This is in part due to the juxtaposition of geological processes operating over geological time scales onto ecological processes operating over much shorter intervals. The geological record does tell us that IPCC predictions for 21st Century climate change for sea level and sea surface temperature (SST) fall within the rates and magnitudes experienced in the recent geological past of living coral reef assemblages, but for $CO_2$ they do not. The recent past history of modern coral reefs shows no slowing of reef growth through extreme SST and sea level events (Table 22.1). Ecologists and managers concerned about the vulnerability of reefs to projected rapid climate change must acknowledge the ability of coral reefs to either survive or quickly recover from extreme SST and sea level episodes. Study of the mechanisms through which reef survival or replenishment occurred over these intervals should allow for a better understanding of threats from climate to coral reefs over the next century. Similarly, the modern reef's ability to cope with unprecedented changes in the rates and magnitudes of $CO_2$ must also be seriously considered.

It is clear to us that climate change is coupled with multiple anthropogenic effects that are likely to threaten the global reef system. For the GBR, areas that are less influenced by humans such as the outer GBR are the least vulnerable while inner GBR areas that have suffered more from coastal influences would be more likely to suffer. Ultimately, this is an optimistic assessment since mitigation of local and regional sources of disturbance along the GBR are more easily achieved than mitigating increasing atmospheric concentrations of greenhouse gases.

As a paradox when considered in the context of past abrupt climate change and the apparent lack of permanent deleterious ecological effects, it is clear that marine ecosystems in general, and coral reefs in particular have been able to either survive from or quickly reconstitute after repeated extremes in climate. The mechanisms by which such resilience occurs need to be meted out, along with how that resilience is affected by the anthropogenic stress already imposed on living reefs prior to and concurrent with climate change. What are the mechanisms by which such resilience to climate change might have occurred in the past, and how will this resilience be affected by the anthropogenic stress already imposed on living reefs prior to and concurrent with climate change? For example, how does response to environmental change differ between exposure of pristine reefs to the abrupt climate change in the past versus overfished or polluted reefs today[100]? The El Niño event of 1998 was instructive in that pristine reefs suffered bleaching equally to degraded reefs[140]. However, recovery times were markedly different[105]. What do past abrupt climate change events teach us about the ecological consequences of future climate change on coral reefs? Put another way: what, if anything, is fundamentally different about the global reef ecosystem today compared to the systems that either survived during or re-established after multiple climatic changes? The answer suggested by the historical and geological record is the presence of increasing anthropogenic disturbances.

## 22.3 Summary and recommendations

### 22.3.1 Major vulnerabilities to climate change

One of the major vulnerabilities to climate change for the GBR is abrupt climate change. Most ecologists attempting to come to grips with the implications of climate change to their ecosystems are still envisioning climate change as gradual change associated with increased greenhouse gas emissions, albeit much faster than perceived rates of past change. Ecologists may be dramatically underestimating the magnitude, speed and extent of past climate change[3,4,5] (Table 22.1). It is now becoming increasingly clear that sub-orbital and abrupt climate change events are part of natural climatic cycles. We need to better understand what the relationship is between the triggers of these events and rising climate change and what the effects will be on coral reef communities. Another key climate component is the dramatic rate of increase in $CO_2$ levels. Though levels of $CO_2$ have been substantially higher in the geological past, the ability for living corals and associated reef taxa to cope with present dramatic rates of change is unknown.

### 22.3.2 Potential management responses

Our recommendations concerning the vulnerability of coral reef communities of the GBR to projected change in climate over the next century are based on three pillars that summarise the results presented herein: i) The rates and magnitude of sea level and temperature changes over the next century are no greater than those experienced by living coral reefs throughout the past several hundred thousand years, but the magnitude and rates of $CO_2$ rise are much higher than over the same interval; ii) the presence of Pleistocene fossil reefs at localities extending up to 500 km south of the limit to their modern counterparts in Western Australia suggest that, given suitable substrates and water clarity, coral reefs can expand their latitudinal range during episodes of heightened water temperatures (see also southern reef occurrences along eastern Australia[107]); and iii) coral reefs have been substantially impacted by human activities that appear to have accelerated in their intensity. Thus, dramatic changes in the magnitude and rate of change in climate variables coincide with impacted reefs that are heavily degraded by human activities.

#### Recommendations

Our first recommendation is to immediately reduce human impacts on the GBR that are unrelated to climate change. Planned response to projected climate change on reefs should aim to increase the ability of coral to respond positively. We know that it is possible for 'natural' coral reefs to withstand severe changes in climate over short periods, so this will best be accomplished by reversing and mending reef degradation that has already occurred. This view stems not from denying the potential for large-scale mortality as a result of climate change; but is based on the response of reef growth through similar past intervals as evidence that the ecosystem has the potential to be resilient to climate change. Reefs have repeatedly assembled after multiple periods of moribundity, even on the GBR[123]. Therefore, even though present day coral distributions might reflect the upper thermal tolerances of corals[42], the larger pattern suggests that even large-scale mortality may not result in the permanent demise of coral reefs worldwide over a *geological* timescale. One has to entertain the possibility that a more global view of reef distribution provides insurance against reef extinction when heightened temperatures and $CO_2$ occur during climate change.

One scenario that might have resulted in continuity of reef development over abrupt climate change events occurred during the last interglacial period. Extension of coral reefs during the last interglacial resulted in the occurrence of vibrant, diverse coral reefs as far south as Rottnest Island in Western Australia and Evan's Head[107] in New South Wales. Let's imagine that past spikes in temperature resulted in a significant increase in coral bleaching events and greater than 90 percent coral mortality in the previously defined reef areas at low latitudes. New areas south of the original extension of coral reefs may have acted as relict populations seeding reefs further north, leading to subsequent sustained recovery of northern Australian reef populations. Southern populations have a precedent for re-seeding northern reefs on the GBR during glacially-induced sea level rises (since deeper southern GBR reefs probably supported reef growth sooner than the shallower shelf where northern GBR reefs reside), for example from the last glacial maximum 18 to around six thousand years ago. Clearly, extension of GBR corals south of their present ranges will depend on a myriad of factors, including substrate availability and ocean acidity. Regardless of the efficacy of this scenario, the important point is that past reefs, even on local spatial scales, have survived or quickly recovered from past climate fluctuations. Again, the important differences in the modern setting are anthropogenic degradation and heightened rates and magnitudes of $CO_2$.

Our second recommendation is to re-focus management away from maintenance of the status quo ('our GBR – let's keep it great') to active restoration of reef resilience ('our GBR – let's get it back'). The best way of ensuring the successful transition of GBR reefs through abrupt or gradual climate change is to restore the ecosystem to good health. It is apparent that this is not presently the case for the GBR[100,101,13,36]. Therefore, management actions cannot only protect areas of the reef from further degradation. Instead, management must now take proactive steps that recover losses and reverse the trajectory of decline[101]. Efforts toward large-scale and whole-sale restoration of both herbivore populations and nearshore water quality represent the most immediate challenges.

We recommend positive actions that adhere to a 'no-regrets' policy and provide benefits regardless of the magnitude, rate or degree of future climate change[88]. Both scientific and political activities should be geared toward enhancing the ability of the GBR to weather the coming climate storm; if no such storm arises, then such activities will still have been favourable to the intelligent management of one of Australia's leading tourist attractions and, more importantly, one of it's national treasures. We can think of no better 'no-regrets' policy than reversing the trajectory of decline of the GBR, restoring the majestic trophic structure that Captain Cook took in when first plying the emerald seas of this brave new world.

### 22.3.3 Summary

Some of the physical changes that are projected to occur in the coming century[64] have occurred repeatedly throughout both the past two million years of the Quaternary period and in the more distant past, while others have not. Reef coral communities in the distant past rebounded from decimation resulting from climatic events that affected the global marine biota. Recovery intervals varied from four to 100 million years, during which time framework building organisms were largely absent from reef ecosystems. More recently, Quaternary coral reef development either proceeded undeterred throughout climatic changes or recovered so quickly as to leave no record of their demise. The major difference between past reefs and those confronting climate change in the next

century is that today's reefs have been preconditioned by human impacts such that the frequency of disturbance might have decreased their resilience to perturbations[63]. Thus, the GBR is vulnerable to global climate change not only because of the physical changes in environmental conditions, but also because these changes will be brought upon an already stressed ecosystem.

### 22.3.4 Further research

Consideration of acclimation and adaptation of coral reefs in the context of new advances in climate research and anthropogenic stress provides a significant step forward in the inter-disciplinary synthesis and prediction of coral reef response to climate change. For their part, coral reef ecologists and physiologists are engaged in a lively debate over how climate change might impinge on the survival and growth of coral reefs. The debate encompasses views ranging from extirpation[59], to change but not extirpation[63], to intact survival[26,10,11,113]. Nowhere in the debate is there a consideration of 'abrupt climate change' in the geological past (which reefs have either survived or quickly replenished from) or future (which will occur to anthropogenically stressed reefs[100]). Current debates on coral/symbiont acclimation or adaptation need placement in the context of historical response of natural reefs to 'abrupt climate change' vs. future response on modern, anthropogenically stressed reefs.

One of the great challenges is to generate information on the role of habitat degradation and loss of biodiversity on the resilience of GBR communities. In the face of imminent climate change there will be cries from every field of inquiry for immediate research needs. An immediate concern is an understanding of how to foster resilience of already multiple-stressed coral reef communities (by anthropogenically-induced sources of mortality and habitat degradation) under impending predicted climate change. In other words, we need a better understanding of how resilience can be maintained and improved in impacted coral reefs. For example, the diversity-stability relationship has been established at both ends of the spatio-temporal spectrum (short observation intervals and experimental scales to millions of years and global scales). Understanding this relationship at intermediate scales – the range of long-term ecosystem management – will facilitate our ability to foster resilience. An understanding of improving resilience is probably the best defence we can have over a highly variable and potentially unpredictable future.

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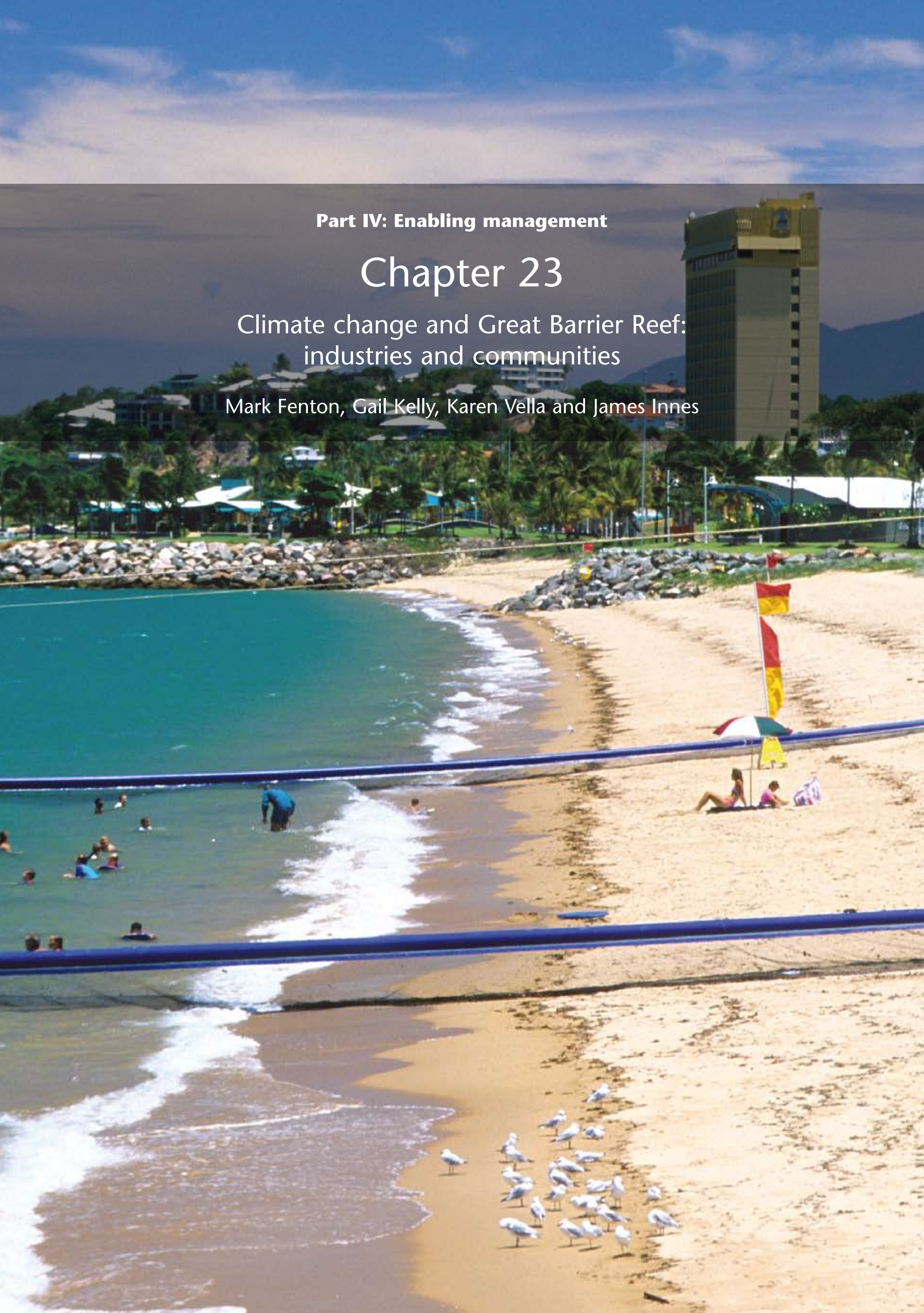

Part IV: Enabling management

# Chapter 23

## Climate change and Great Barrier Reef: industries and communities

Mark Fenton, Gail Kelly, Karen Vella and James Innes

## 23.1 Introduction

Climate change is driving shifts in environmental conditions that, together with other human pressures, are impacting the Great Barrier Reef (GBR). Individuals, communities, and industries in the GBR catchment depend directly or indirectly on the GBR for ecosystem goods and services. These take the form of direct economic benefits (including commercial activities such as tourism and fishing), social services (including recreational activities and cultural linkages) and environmental services (including shoreline protection from barrier reefs and mangrove stands).

Although there is consensus within the global scientific community about the causes and potential impacts of climate change, stakeholders are less certain about the impacts and effects. Climate change is understood and acted upon as a subjective event that is constructed by different stakeholder groups and imbued with meanings derived from experience and the social and cultural context in which individuals, industries and communities find themselves. Individuals, stakeholders and communities' recognition and acknowledgement of climate change, how they construct and give meaning to climate change processes, and the content of their anticipatory schema in relation to climate change impacts and response, determine their vulnerability, adaptive capacity and adaptation, and resilience to climate change. There is a difference in preparedness amongst different stakeholder groups to climate change impacts.

Uncertainty by stakeholders and diversity in preparedness pose serious challenges for management. Climate change involves considerable uncertainty, the potential for irreversible damage, time lags between cause and effect, a long planning horizon and the need for systemic institutional change[14]. In addition, the GBR catchment is a highly contested environment. Issues include growing populations (which drive demands to access and use environmental resources), multiple and often conflicting value systems, multiple and often conflicting knowledge and belief systems and entrenched intergenerational patterns of resource use. Existing institutional regimes (formal and informal) governing resource use and access have complex structures involving rights, roles and responsibilities for environmental management and institutional change in the GBR catchment can be a long and difficult process. For example, ongoing effort over the past 10 years to improve institutional arrangements governing the Queensland Sugar Industry highlights the difficulties of achieving institutional change in the GBR catchment[17,30,16].

Despite the potential economic and social impacts from effects of climate change in the GBR, there has been only one assessment of climate change and communities and industries in the GBR. This chapter discusses concepts of vulnerability, adaptive capacity, adaptation and resilience, and identifies socio-economic characteristics of communities and factors relevant to understanding the social dimensions of climate change in the GBR. The chapter discusses the recent study by Fenton and Beeden[26] that examined community and stakeholder perceptions and beliefs about climate change and its social and economic impacts in the GBR. It raises a number of core issues associated with the adaptive capacity and resilience of community and industry to prepare for climate change in the GBR catchment. It finds that a single approach towards preparedness and management for climate change is unlikely to have an effective response with all groups. Management responses therefore, need to involve diverse community and industry stakeholders in the GBR catchment in the policy making process.

## 23.2 Definitions of social resilience

The preceding chapters provide detailed assessments of vulnerability, adaptive capacity and resilience in relation to species groups and habitats within the GBR. Before discussing GBR industries and communities, their vulnerability to climate change and stakeholder perceptions and beliefs about climate change in the GBR catchment, it is important to firstly discuss concepts of vulnerability, adaptive capacity, adaptation and resilience as they relate to social dimensions. These terms have emerged out of the ecological sciences and are becoming increasingly interwoven into discourse about the social dimensions of climate change. There are multiple and often competing definitions for these concepts and a number of different explanatory frameworks and definitions underpinning each of these concepts. While it is clear they are related, there is currently little consensus about the nature of these relationships.

### Vulnerability

Definitions of vulnerability are generally based on three broad approaches: i) natural hazards and disasters, ii) social vulnerability, and iii) integration[54]. When adopting a natural hazards approach, the focus is on the actual physical hazard – its type (abrupt or chronic), frequency, duration, probability, intensity, severity and magnitude. This is used to determine the vulnerability of the exposed system[12]. Hazard-specific vulnerability is concerned with the amount of (potential) damage caused to a system by a particular event including human exposure to that risk[12]. Vulnerability is usually expressed in monetary cost, human mortality, production costs or ecosystem damage but importantly does not take into account the ability of the system to cope with, and respond to, the hazard when estimating vulnerability[54].

In contrast, social vulnerability refers to the social and political conditions within which a system is embedded[5], as well as the internal characteristics and processes that increase exposure of the system to the hazard – this includes its capacity to cope or respond. Social vulnerability can also include individual and community assessment of the hazard when considering response options and in this way can be described as the readiness of the social system to react to a certain situation[38].

Integrative approaches to vulnerability have emerged more recently from climate change research and necessarily take a systems view. Here vulnerability is both a function of the system's sensitivity and its capacity to cope and adapt, as well as the character, magnitude, and rate of climate variation (hazard) to which the system is exposed[54]. Brooks[12] argues that this is where the confusion with the vast array of similar and related terms, such as resilience, adaptive capacity, coping range, risk and sensitivity most often occurs. In attempting to untangle this confusion, Clarke et al.[18] state that vulnerability is a function of exposure (the risk of experiencing a hazardous event) and *coping ability* (which they equate with social vulnerability) that is, in turn, a function of resistance (ability to absorb impacts and continue functioning) and resilience (ability to recover from losses after an impact). Using a rural livelihoods framework at a household level, Ellis[23] describes vulnerability as high exposure to risk from both the external threat (hazard) and the level of internal coping capacity (assets and social support systems).

### Adaptation and adaptive capacity

In relation to climate variability and change, the Intergovernmental Panel on Climate Change[31] defines adaptation as an adjustment within a system's ecological, economic or social sub-systems in response to actual or perceived change. Adaptation can be either autonomous (reactive response after initial impact without directed intervention from government agencies) or planned (anticipatory or reactive before impacts manifest).

Adaptive capacity is described as the ability or capability of a system to modify or change its characteristics or behaviour to cope better with actual or anticipated stresses[12]. Importantly, adaptation response can focus on building the capacity of individuals, groups and communities to adapt to change, as well as implementing adaptation strategies[3]. Evidence also suggests that previous exposure to climate events including cyclones[13] and bushfires[45] can lead to greater adaptive capacity through better preparedness.

### Resilience

Walker et al.[52] define resilience as the potential of a system to absorb change and remain in a functioning state including the ability to reorganise itself following change. Resilience in social-ecological systems is concerned with how much shock the system can absorb and still remain within a desirable state, the degree to which the system is capable of self-organisation, and the degree to which the system can build capacity for learning and adaptation[28]. While resilience generally refers to a system's capacity to respond and bounce back, Folke's last point is critical; resilience of social systems includes adaptive capacity. This is emphasised by Paton[44] in the context of response to hazards, where he argues that social resilience is more than merely returning to a previous state, it includes the capacity of people and communities to learn and/or to recognise and benefit from the new possibilities that change brings.

The relationship between vulnerability and resilience is not clear. Some researchers see resilience and vulnerability as the other side of the same coin[13,31]. However, others argue that vulnerability factors co-exist with resilience characteristics that facilitate adaptive capacity[44]. Thus, resilience does not necessarily imply invulnerability; social resilience is relative (not absolute) and will change over time and vary in different situations.

While the concepts of vulnerability, adaptive capacity, adaptation, and resilience are useful in understanding human response to climate change, they need to be integrated and substantially grounded in the social and cultural context of the GBR.

## 23.3 GBR industries and communities

The GBR and its catchment is an integrated social-ecological system that is in a constant state of change, and which has a significant and long history of system interdependence and interaction.

The catchment adjacent to the GBR has a population of approximately 850,000 residents that is projected to increase to one million by 2026[19] (Figure 23.1). Along the length of the GBR, there are 21 local government areas and the major urbanised centres of Cairns, Townsville, Mackay, Rockhampton and Gladstone.

Management and protection of natural resources in the adjacent GBR catchment is the primary responsibility of the Queensland Government and seven regional Natural Resource Management (NRM) organisations, from Torres Strait in the north to Burnett Mary in the south (Figure 23.2). Within the last two to three years each NRM organisation has developed a natural resource management plan and investment strategy for the management of natural resources in their region, which includes estuarine, coastal and marine habitats. In the 2003–2004 financial year, A$12.2 million was spent by regional NRM organisations on the management of natural resources from Natural Heritage Trust funds alone.

***Figure 23.1*** *Great Barrier Reef catchment areas and urban centres*

***Figure 23.2*** *Regional Natural Resource Management boundaries within the GBR catchment*

The GBR and adjacent catchment also supports considerable economic activity. The total (direct plus indirect) economic contribution of tourism, commercial fishing, and cultural and recreational activity in the GBR towards Australian gross product was A$6.9 billion in 2005–2006[1] (Table 23.1). Tourism dominates these economic contributions within the GBR. For value added and gross product, tourism's share is about 84 to 87 percent and for employment, tourism's share is about 81 to 84 percent[1]. This creates significant economic flow-on benefits to the broader population and local economies within the catchment. There is considerable diversity in tourism activities, which include: cruise ships, kayaking, diving and snorkelling, day tours, bare boat charters, fishing charters and water sports. In 2006, there were 1,831,609 visits to the GBR[a] (Figure 23.3).

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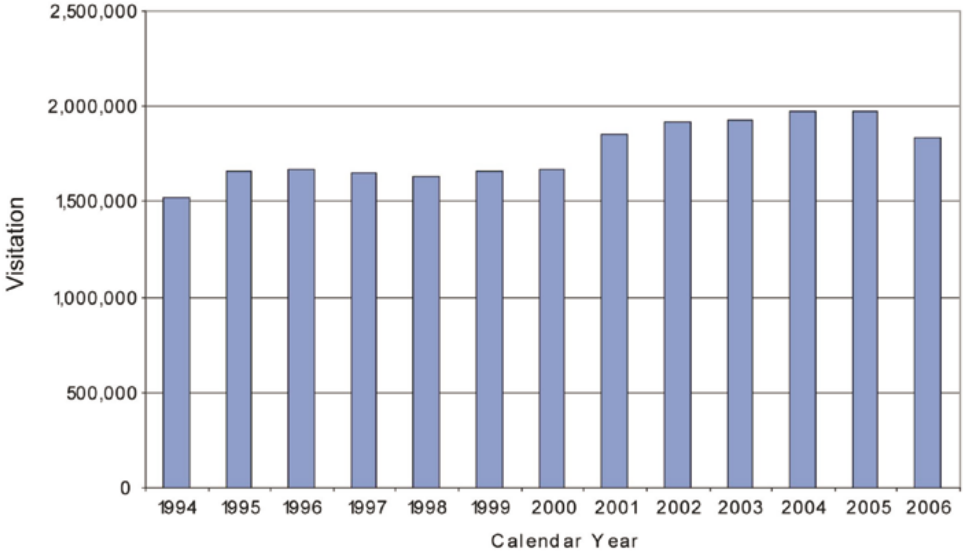
[a] Great Barrier Reef Marine Park Authority (2007) www.gbrmpa.gov.au

**Table 23.1** *Direct plus indirect contributions of selected Great Barrier Reef Catchment Area (GBRCA) activities to Australia, 2004–2005 and 2005–2006*[1]*. Money values in millions of Australian dollars and full time equivalent by the thousand (FTE 000)*

| | 2004–2005 | | | 2005–2006 | | |
|---|---|---|---|---|---|---|
| Total contribution (direct plus indirect) | Total value added ($) | Total GDP ($) | Total employment (FTE 000) | Total value added ($) | Total GDP ($) | Total employment (FTE 000) |
| Visitors from GBRCA | 773 | 948 | 10 | 750 | 923 | 9 |
| Visitors from rest of Qld | 724 | 879 | 8 | 659 | 803 | 8 |
| Interstate visitors | 1,282 | 1,559 | 14 | 1,661 | 2,019 | 18 |
| By GBRCA residents for travel outside GBRCA | 211 | 254 | 2 | 228 | 276 | 2 |
| International visitors | 1,528 | 1,856 | 17 | 1,633 | 1,982 | 18 |
| **Total tourism** | **4,518** | **5,496** | **52** | **4,932** | **6,004** | **55** |
| Commercial fishing | 273 | 288 | 2 | 238 | 251 | 2 |
| Recreational activity (net of tourism) | 544 | 624 | 9 | 542 | 623 | 9 |
| **Total contribution to Australia** | **5,335** | **6,408** | **63** | **5,712** | **6,877** | **66** |

**Figure 23.3** *Reef-wide total visitors to the GBR by year*[b]



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[b] Great Barrier Reef Marine Park Authority (2007) www.gbrmpa.gov.au

In the past several years, the tourism industry has experienced significant changes in visitation to the GBR and has had to contend with changes in the quality of many reef sites affected by coral bleaching, poor water quality and the impacts of the crown-of-thorns starfish.

There are five main commercial fisheries operating in the GBR with a total gross value of A$251 million for production in Australia in 2005–2006[1]. In addition, there are estimated to be 800,000 recreational fishers in Queensland with those using the GBR catching an estimated 3500 to 4500 tonnes per year.

Along the coast from the Torres Strait to Bundaberg, there are some 70 Traditional Owner groups with an interest in, and connection to, coastal land and the GBR. In working with Traditional Owners, the Great Barrier Reef Marine Park Authority (GBRMPA) has identified 27 management areas along the GBR coast based on the way Traditional Owners work administratively within their groups and tribal lands. Traditional Owners associated with several regional NRM organisations have developed plans for the management of their country that has included the coastal and marine environment[c]. Access to country, maintaining cultural identity, and the continued maintenance of traditional hunting rights are three critical issues of current concern to Traditional Owners within the GBR catchment.

Climate change will affect communities and industries in the Great Barrier Reef Catchment Area[d] (GBRCA) that depend on natural resources for economic, social, and cultural wellbeing. Communities and industries within the GBR each face different industry, community and environmental issues and have differing access to resources. It is important to identify community and industry vulnerability, and if possible, social resilience to climate change and how GBR communities and industries might respond and adapt to climate change impacts. This information will assist policy makers develop policy processes and institutional tools that are appropriate and effective in addressing climate change issues given the social characteristics of communities and industries.

## 23.4 Vulnerability to climate change

Climate-related events such as floods, droughts and fire impact on the general public, businesses and the government sector by positively or negatively affecting agricultural production, forestry, tourism, the health and viability of fisheries and the quality and quantity of water resources[47]. The broad potential impacts of climate change on Australian agriculture, forestry and fisheries, settlements and industry, and human health have been identified by Pittock[47]. Information on the vulnerability of communities, and industries and the general population within the GBR is more limited.

From an industry viewpoint within the GBR, reef-based activities within the marine tourism industry are particularly susceptible to the effects of climate change, namely loss of coral reef due to bleaching, and changes to abundance and location of fish, marine mammals and other iconic species. Increasing frequency and intensity of storms and cyclones will impact passenger and tourism operator safety,

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[c] Wet Tropics Aboriginal Plan Project Team (2005) *Caring for Country and Culture – The Wet Tropics Aboriginal Cultural and Natural Resource Management Plan*. Rainforest CRC and FNQ NRM Ltd Cairns
Traditional Custodians of Country in the Burdekin Dry Tropics Region (2005) *A Caring for Country Plan*. Burdekin Dry Tropics Board, Townsville

[d] GBRCA: Great Barrier Reef Catchment Area. The GBRCA include islands within the Great Barrier Reef Marine Park plus large areas of mainland Australia, mainly east of the ridge defined by the mountain summits of the Great Dividing Range

industry seasonality (and opportunities for reef experiences), tourism infrastructure and associated tourism industry development. The fishing industry is also heavily dependent on climatic conditions. Changes in ocean circulation, wave generation, cyclones and air and sea temperature may impact productivity with resultant effects for the fishing industry and aquaculture. In addition, declining water availability will greatly impact catchment industries such as agriculture, horticulture and mining, as well as the general population[4].

Human health and coastal development are other ways in which the GBR social system is vulnerable to climate change. Health risks related to climate change include heat-related stress and death, increases in water and vector borne diseases, and declining water availability. Towns and associated infrastructure will be affected by changes in demand for energy, changing land values and land use systems, changing liveability and lifestyle, and by direct impacts on buildings and structures from extreme weather[4].

Climate change may also impact cultural systems in Queensland. Although the extent and impact of climate change on traditional marine and land resources is unclear, a decline in the availability of traditional resources could disrupt customs and practices, leading to a loss of knowledge, skills and culture. Similarly, climate change may also impact recreational use opportunities in the GBR such as fishing and boating. This may lead to changes and possible reductions in traditional and indigenous identity and belonging, and impact quality of life for non-indigenous Australians through reduced cultural and recreational opportunities.

When considered at a broader level, the social and economic effects of climate change in the GBR region may include economic and social instability. This will be due to changing industry structure and presence, changing population and demographic characteristics, coastal vulnerability due to infrastructure pressures, human health risks, storm events, and pests and disease[20].

These social and economic effects are likely to also result in changed land use and other activities as industries, communities and other sectors respond to climate change. Storm events, pests and disease, coastal vulnerability, industry vulnerability, and population change will put different pressures on marine and terrestrial resources.

Land use changes that could occur include the intensification of agricultural activities (eg horticulture) and reduction in broad scale agriculture, growth of less climate-dependent industries such as mining, and growing pressure for residential development in upper catchment areas.

Overall, climate change, as an environmental risk, poses uncertainty for management and decision making for all stakeholders in the GBR. In an environment characterised by ecological and social uncertainty, adaptive strategies are required. Adaptive management approaches are flexible and treat management as an iterative process of review and revision in response to unexpected events, the accumulation of knowledge, and experiential learning. However, in order to develop management approaches and strategies that are appropriate in the social and economic environments within the GBR catchment, we need to better understand community and stakeholder perceptions and beliefs about climate change and its social and economic impacts in the GBR.

## 23.5 Exploring the impacts of climate change on communities and industries

There is limited research and literature assessing the impacts of climate change on communities, industries, and stakeholder vulnerability and resilience in the GBR. A study by Fenton and Beeden[26] of stakeholder beliefs about climate change in the GBR catchment is the only specific social assessment of climate change issues in the GBR. Outside the GBR, global climate change literature predominantly explores public understanding of climate change and there is limited literature describing social vulnerability and responses to climate change. This section will briefly review climate change literature relevant to understanding the impacts of climate change on communities and industries in the GBR.

### Public knowledge of climate change

Although the global scientific community speaks out essentially as a unified voice concerning the anthropogenic causes and potential devastating impacts of climate change at a global scale, many stakeholders still harbour considerable uncertainty about the problem itself[10]. Moreover, *'far from being stable and unitary, public understanding of environmental issues are 'fragmented and contradictory' and are used to convey a multitude of meanings concerning the relations between society and nature'*[15].

Public knowledge of climate change is commonly dismissed as incorrect and confused and the lack of public understanding of climate change attracts significant attention from all sides of the policy debate[15]. Community and industry understanding of climate change relates to people's knowledge of physical environmental processes as well as relationships between people and the environment. People's understanding of climate change involves diverse fundamental moral and religious views on the relationship between people and the environment, the rights of nature and other species, people's rights to change or manage nature, and society's responsibility for future generations[15].

There is broad variation in people's beliefs or 'mental models' about climate change[8]. Even modest social studies involving carefully conducted and analysed interviews on a small scale can identify the basic features of mental models and provide the necessary information to underpin public involvement in management[8]. An assessment of communication strategies of human health risks associated with climate change by Bostrom and Fishhoff[8] found that communication must reflect:

- The science of the risks they are describing
- The mental models that individuals bring to understanding that science
- The decisions facing individuals

Communication must focus on the information most relevant to those decisions, and present information in a way that is compatible with decision maker's information-processing strengths and weaknesses.

### Measuring vulnerability

Measuring community and industry vulnerability to environmental change, such as climate change, is difficult because of the limited availability of useful research and data sets. Data sets that are broadly available to measure social and economic characteristics include the population census; however, these broad repeatable data sets are problematic for measuring vulnerability to environmental change because it is very difficult to identify the causal factors of change in socio-economic characteristics.

Problems with using population characteristics to measure community vulnerability to environmental change are identified in an assessment of community and industry vulnerability to natural hazards and disasters such as cyclones, storm surges and floods in Northern Australia[36]. One issue associated with using census population characteristics to measure community vulnerability relates to the size of the collection district. Collection district boundaries are small and geographically based; thus populations vary between districts and between censuses within the one district. Since collection districts are small, population data needs to be aggregated to avoid the identification of individual people. This makes spatial and temporal comparison difficult; socio-economic detail and precision is lost through the aggregation process, and causality of population migration in and out of a collection district is difficult to relate to issues such as environmental change[36].

Another issue relates to standardising data for comparison[36]. By standardising census data, the raw figures of numbers of people are lost when undertaking statistical analysis. For example, a high proportion of the elderly or single parent families may indicate high vulnerability for particular Collection Districts, whereas total numbers of these vulnerable groups may be much higher in Collection Districts with larger populations[36]. This is problematic when attempting to determine the impacts and effects of environmental change on communities and industries.

In addition, the Australian Bureau of Statistics socio-economic indicators for areas and weightings into indicators of socio-economic advantage or disadvantage are statistically reliable but have not been selected to yield information about vulnerability and resilience to environmental change. For example, *'persons aged 15 and over with no qualifications'* are identified as having a greater socio-economic disadvantage than *'dwellings with no motor car'*, however the relationship between these characteristics and disadvantage and environmental change is not clear[36].

## Adaptation

A review of social-ecological resilience to climate change in a Canadian Western Arctic community identified that societies can adapt to climate change at multiple scales. This study found that societies can implement short-term adaptive strategies to cope with climate change. In the case of the Canadian Western Arctic community, short-term adaptive strategies included changes in land-based activities such as switching species and adjusting 'when, where and how' local people hunt. The study found that societies can implement long-term cultural and ecological adaptations in response to highly variable and uncertain environments, including the flexibility of seasonal hunting patterns, detailed traditional knowledge of the environment that enables the diversification of activity, and inter- and intra-community sharing networks[7].

The study found that the range and extent of both the short- and long-term responses defined the resilience of the community[7]. In terms of responding and adapting to climate change, it is not the gradual change that is important, but rather the disruptions due to uncertainties and extreme events, especially those that exceed a system's absorptive capacity. However, the study also found that not all extreme events are dangerous and not all ecological surprises are negative from the local point of view[7].

### Great Barrier Reef communities and industries

Despite the important relationship between societal views and perspectives about climate change and public policy, relatively little is known about community and industry understanding and perceptions of climate change, particularly in the GBR.

Fenton and Beeden[26] undertook an analysis of qualitative interviews with 44 stakeholders including individuals from regional NRM organisations, State and Local Government, Traditional Owners, the tourism industry, the commercial fishing industry and the recreational fishing sector[e]. The study identified community and industry perceptions of climate change and perceptions of the impacts and effects of climate change in the GBR.

An interpretive approach was used to analyse interviews. This approach assumed that human understanding and action is based on the interpretation of information and events by the people experiencing them[49]. The information that people have about events is organised as a schema[42], which is an internal working model or cognitive representation through which an individual organises and describes the information they have about the world. Any individual's cognitive schema is in a constant state of change and adapts as new information about the world and the events they are experiencing are assimilated and/or accommodated into the existing schema[46]. The schema holds what is commonly referred to as a person's knowledge or beliefs about a concept or issue, and it is the schema itself that determines how individuals respond and behave in situations. The importance of cognitive schemas[f] is identified by Niemeyer et al.[43], who state in the context of climate change that *'facts do not determine behaviour so much as perceptions about those facts'.*

The Fenton and Beeden study did not seek to critically evaluate the knowledge of beliefs of participants in terms of their 'correctness', or whether they accord with existing scientific evidence or some objective assessment of environmental condition. It sought to understand the beliefs that are reported in their own right, independent of any objective yardstick that might be used as a measure of 'correctness' as it is the beliefs themselves and the organising schema in which they are embedded that are the best predictors of human attitudes, behaviour and adaptive capacity. We will now report the key findings of this study.

## 23.6 Stakeholder understanding of climate change in the Great Barrier Reef

Fenton and Beeden[26] examined community and stakeholder perceptions and beliefs about climate change and its social and economic impacts in the GBR. It identified three clusters of issues associated with participants understanding of climate change:

i) The recognition and acknowledgement of climate change

ii) Understanding climate change and climate change processes

iii) Identifying the consequences, impacts or responses to climate change

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[e] A detailed description of the methodology and qualitative research findings is provided in Fenton and Beeden[26]

[f] In other literature, cognitive schemas are also referred to as mental models[33, 53]

The three clusters of issues are not independent and there are cumulative and causal (reciprocal and unidirectional) associations between each of the issues clusters. For instance, the study found that someone who does not recognise or acknowledge climate change will often also possess a relatively simple cognitive schema[21] about the climate change process and in turn will have difficulty identifying any consequences or impacts of climate change. In contrast, those who recognise or acknowledge climate change will often possess relatively complex cognitive schema to describe climate change processes and its consequences or impacts.

In addition, while it is important to understand and describe the schemas people hold in relation to climate change and the impacts of climate change, it is also important to understand what these schemas say in relation to the framework of social resilience and more specifically the key concepts of vulnerability, adaptive capacity and resilience.

Some care is also required in distinguishing the use of schemas as guiding an individual's behavioural response to climate change from the use of schemas to describe behavioural response to climate change. For example, a commercial fisher may possess a relatively complex schema about climate change processes, the content of which guides their behaviour and response to climate change. The same individual may also use that schema to explain the resilience or vulnerability of their industry to climate change. In the former case, the schema is directing their behaviour while in the latter it is being used as a basis from which they can report their attitudes and beliefs about climate change.

### 23.6.1 Recognising and acknowledging climate change

The recognition and acknowledgement of climate change has to be understood within the context of each individual stakeholder's experience and knowledge of the marine ecosystem and the institutional and organisational structures associated with its management. Across the different interview participants, there was considerable variation in the level of experiential and scientific knowledge about the marine ecosystem and climate change. At one extreme, commercial fishers, Traditional Owners and to a lesser extent recreational fishers and tourism operators often had very detailed local knowledge and belief systems about how the ecology of the local area functioned.

In contrast, and although there are exceptions, much of the knowledge about marine ecosystems and climate change amongst Government agencies and regional NRM organisations was based on 'scientific data' and the knowledge of 'experts', which had been provided by others. The expression of this type of knowledge tended to be more abstract, general and applicable at a macro- rather than micro-scale. The study found that many in these organisations indicated a paralysis of action because of the lack of data or scientific knowledge on which to plan and develop effective strategies for climate change. In addition, and as climate change had become a topical area of scientific inquiry, several participants also expressed the view that there was no cohesion to the scientific research being undertaken.

While scientific knowledge provides important information about managing and responding to climate change, the type of experiential local knowledge held about the marine environment has obvious implications in relation to how people respond to climate change. The following quotation indicates how one commercial fisher conceptualised the causal relationship between droughts on the land and reduced catch rates.

> *'…if it is drought on the land we always say we have a drought at sea too…the water seems to be warmer. The boys always say the temperature is a lot warmer and it needs good rain to oxygenate the water… in long dry hot periods the fish go down deeper and your catch rate goes right down.'*

While commercial and recreational fishers provide numerous examples that illustrate their beliefs about how ecological processes influence their fishery, there were also numerous examples of how ecological process had changed across time. While there was considerable consensus that significant change had occurred in the marine ecosystem, there was in contrast, often little consensus in the beliefs about the causal attributions for these changes and whether these changes could be attributed specifically to climate change processes.

While some participants attributed the changes they had experienced to climate change processes, several participants also considered these changes to be 'natural' processes or attributed the changes to other human actions such as overfishing, pollutants, sediment runoff and the use of agricultural fertilisers. As one Traditional Owner stated:

> *'I've always blamed the aerial sprays, the fertiliser in the land…the seepage from waterways here and it takes it to the reef…especially in the warmer climate.'*

Some participants described a more complex belief system, which illustrated the causal relationship between the changes they were observing and the processes of climate change. In effect, these participants had developed their own cognitive model of the impacts of climate change that described for them the interrelationship between climate change process and ecological systems. As shown in the following quotation from a recreational fisher; climate change produces less rain, which produces less runoff, which leads to fewer sediments, which in turns leads to an increase in water clarity and an improvement in the spearfishing environment.

> *'…less rain…we're spearfishing under the lighthouse now at the mouth of the river where that waters never been clean ever because of sediments and that that came out…now you can actually spearfish there.'*

Some Traditional Owners also emphasised the cyclic nature of natural processes, including climate change itself, and emphasised that while there may be significant impacts, their traditional stories tell of times when sea levels were much lower than today with many sacred and significant places now located undersea.

While there was considerable variation amongst participants in the attribution process, the attribution of change to climate change processes also depended upon the acknowledgement of climate change in the first instance. The acknowledgement of climate change appeared to be related to three core factors:

i) Beliefs about the uncertainty of scientific evidence

ii) Previous impact predictions (ie Y2K and SARS)

iii) Trust in organisations and institutions

Perhaps the most common issue associated with the acknowledgement of climate change was the belief that since there was uncertainty within the scientific community and amongst experts about climate change, lay people could only be expected to express an equal level of uncertainty about climate change.

> *'My understanding of the science is that the scientists don't really know what is going to happen with fish numbers and with fisheries as a result of climate change. They don't know that…so how should I know.'*

Several participants also indicated that there had been warnings and predictions about the impacts of other catastrophic events in the past, such as the Y2K bug and SARS. The predicted impacts from these events had not occurred and they questioned why climate change impacts would be any different. This phenomena is similar to the 'crying wolf syndrome'[11] reported in the hazard perception literature, in which repeated false alarms may reduce the credibility of warning information and increase the vulnerability of populations to hazard events.

The uncertainty amongst experts and the failure of past predictions was reflected in some participants as a general lack of trust in science[32,37]. This was also identified by Fenton[24,25] and is becoming an increasingly common theme within rural and resource-dependent communities. A large survey of community attitudes towards risk undertaken in the United Kingdom in 2003 showed that in relation to climate change, 71 percent of the population trusted scientists working for universities or environmental groups as compared to only 42 percent trusting scientists who worked for Government[g].

In addition to a lack of trust in science, amongst some participants there was also a lack of trust expressed in the organisations that were advancing climate change as an issue[2]. Amongst some commercial fishers, and to a lesser extent recreational fishers, there was some cynicism about climate change impacts and a belief by many that the GBRMPA was raising this issue as another mechanism through which fishing effort on the reef could be reduced.

While some participants reported a lack of trust in the science and resource management organisations, others including many from the tourism industry, regional NRM organisations and Government expressed a contrary view of having considerable trust in the scientific community, management agencies and the science being undertaken.

Some participants didn't acknowledge climate change or didn't attribute climate change to the changes they were experiencing in the marine environment. There were others however, who not only acknowledged climate change as occurring, but also attributed the changes they were experiencing to climate change processes. To some extent those who had experiential knowledge[h] of changes in the ecology of the marine environment, tended to be more likely to report the immediacy of climate change impacts and that those impacts were occurring now. In contrast, amongst those with limited experiential knowledge of ecosystem change and who based their knowledge on independent scientific evidence, there was a tendency to view climate change as something that would happen as a scenario in the future. It may well be that those with greater experiential, local and day-to-day knowledge of the ecology of marine ecosystems are simply able to detect some of the more subtle changes than those without this knowledge. This noted however, the day-to-day use of technologies (eg irrigation for agriculture) may mediate the relationship between an individual and their knowledge of the local environment.

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[g] Ipsos MORI (Market and Research International) (2003). Trust in the Government Low. www.ipsos-mori.com/polls/2002/uea.shtml

[h] Experiential knowledge is defined as knowledge gained through 'affective and cognitive transactions with the biophysical and built environments[48], p443) or the process of direct interaction with environment through which meaning is discovered[6]

### 23.6.2 Conceptions of climate change

To understand how individuals, industries and communities prepare for and respond to climate change, it is critically important to understand how climate change is conceptualised and understood. In broad terms, we can ask: what is the content of people's cognitive constructions or schema representing climate change and how does this influence vulnerability, adaptive capacity, adaptation and resilience as expressed through preparedness and capability to respond? Of course, such an approach invokes a constructivist as opposed to a realist analysis[51], emphasising that humans prepare and respond not to 'real' or objective climate change processes, but to their own construction of climate change. This perception of climate change is influenced by a wide range of individual and socio-cultural factors. For instance, research on the use of affective and cognitive heuristics[35,50], social leaning theory[22] and explicit mental models of change events, all indicate that the construction or representation of risk is important in understanding both preparedness and response.

As indicated in the previous section, the schemas individuals develop for climate change processes are based on and drawn from multiple sources of information, including both experiential knowledge and 'expert' information. However, as several regional NRM organisations indicated, there is a significant lack of scientific information about climate change, particularly at the local level, with many people simply being uninformed by science or attempting to fill the gaps they have in their knowledge through their own experience and beliefs about climate change. In addition, several participants had considerable difficulty in conceptualising and understanding the breadth of climate change processes and the potential impacts of climate change. This was particularly so when they considered the longer-term scenarios and may well explain why many of the participants interpreted climate change in the context of their current or recent past experiences.

Participants did not conceptualise climate change as a series of independent events, but in many instances described climate change as a series of interdependent and causally connected events occurring within the environment. The following core climate change processes were identified by participants[i]:

- Less rainfall (drier climate)
- Increase in land temperatures
- Increase in sea temperatures
- Changes in runoff and sediment flows
- Increase in water clarity
- Rise in sea level
- Changes in salinity
- Increase in the frequency and intensity of cyclones

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[i] It should be noted that as this is not a survey of stakeholders or interest groups, it is not possible to identify the frequency or commonality of occurrence for these beliefs

Many participants described the interdependence of these processes. For example, with less rainfall there would be less runoff, which in turn would increase the salinity of the inshore marine environment. Similarly, with a rise in sea level, there would be an increase in erosion leading to increased sedimentation and runoff that again would impact on the marine ecosystem.

What was important for many participants was the magnitude or scale of climate change. While it was acknowledged by many that these processes would occur, there was significant variation across participants in their beliefs about the scale or magnitude of climate change. The following quotation illustrates a belief that the impacts of increases in sea temperature will be negligible.

> *'I can't imagine a one degree change in the average sea temperature can be that critical. Really…the water out here in winter goes down to about 19 degrees most winters…summer it can be 30 degrees. An enormous differential that the animals and plants already tolerate.'*

In contrast, for some participants, the impacts of climate change elicit a near panic response as is evident in the following quotation.

> *'…it is a profound affect…what people are saying by 2040…forget it…we are going to be in deep trouble by then… It's at a runaway point very soon. Its almost scary what will happen. Rainforests are affected, sea levels are affected, coral is affected, our fishing grounds, our farming, our climate, ourselves, our health and of course as that starts to run away so will law and order be effected.'*

### 23.6.3 Impacts of climate change on GBR social systems

Beliefs about the impacts of climate change focus on impacts to the marine ecosystem as well as impacts to social and economic systems. Impacts to the marine ecosystem were essentially the secondary or higher order ecological impacts of climate change, which in turn were seen to impact on the dependent social and economic systems. It was clear, as discussed elsewhere, that amongst those participants who acknowledged climate change, each participant possessed a cognitive model or schema which identified the climate change process and the causal attributions describing initial and flow-on impacts through ecological and social-economic systems.

While there was some commonality across participants in the content of individual's cognitive models of the impacts of climate change, there were also significant differences in the breadth and depth of knowledge about the potential impacts of climate change. The state of an individual's cognitive representation of climate change impacts was in some cases similar to the patchy state of scientific knowledge about climate change, as expressed by one regional NRM body.

It is often argued that the effectiveness of societal responses to climate change depends on how well it is understood by individual citizens[9]. However, it is also argued that rather than focus on the provision of information, policy efforts should address the social and institutional barriers that hinder community and industry involvement in addressing climate change[15]. The purpose of defining individual beliefs about climate change in the GBR is to support the development of policy processes and institutional tools that are appropriate, given the social characteristics of communities and industries, and effective in addressing climate change issues. Therefore, the following discussion identifies individual perceptions and beliefs about ecological, social and economic impacts, as well as impacts of climate change on industry in the GBR.

## Ecological impacts

A common ecological theme amongst many participants was that warmer sea temperatures would be the primary climate change process that would give rise to an increase in the incidence of coral bleaching and changes in the geographic distribution of marine species. As might be expected given the media attention, coral bleaching was a commonly reported impact of climate change. Two issues were raised in relation to the ecosystem impacts of coral bleaching. Firstly, several participants questioned whether coral bleaching should be attributable to the general process of climate change or whether it was episodic and occurred in response to natural variations and changes in sea temperature. Secondly, while the process of coral bleaching was recognised, many participants also believed that corals were sufficiently resilient that they would return after a short time period[j].

> *'…the coral regrowth is quite astonishing. We killed off half the bay's coral reefs in 1991 when a monster flood came down…just obliterated it. You go out there today and you would not know that there was such an event 15 years ago. The coral has actually bounced back within 15 years.'*

Participants indicated the impact of rising sea level and temperatures also raised the possibility of a diverse range of potential ecological impacts, including the inundation of coastal mangroves and other fish habitat areas, impacts on turtle reproduction and breeding through increases in sand temperatures, and changes in the abundance, diversity and distribution of many marine species.

The belief that the marine ecosystem would be resilient to climate change or able to adapt to the effects of climate change was also a common theme identified by many participants. Corals for instance would simply adapt and move into deeper waters that were cooler. Corals and fish alike would change their geographic distribution and begin to grow or frequent areas further south in cooler waters.

While the belief that the marine ecosystem had the resilience and capacity to adapt to change was commonly held, some participants also expressed the view that coral reef habitats did not have the adaptive capacity to respond to the rapidity of the climate change process.

> *'I don't believe the reef is going to be able to adapt quickly enough to climate change, I mean there will be some adaptation but it's not going to be enough to maintain it as a tourist icon or biodiverse paradise as it is at the moment.'*

In terms of addressing the ecological impacts of climate change from the broader perspective of natural resource management, several regional NRM organisations indicated that while they may not have the resources to address the direct impacts of climate change, they could nevertheless improve the resilience of marine and natural ecosystems by addressing other stressors, such as improving water quality through better land use practices.

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[j] Some participants indicated that the GBRMPA in their management of the GBR and through the introduction of the representative areas program, had contributed to the development of a more resilient marine ecosystem and therefore any impacts from climate change would be reduced

## Social and economic impacts

The social and economic impacts identified by participants include beliefs about the potential impacts of climate change to industry, communities and people's way of life. While participants discussed the potential social and economic impacts of climate change at a community or industry level, few participants discussed the impacts of climate change at an individual level. In other words, the impacts of climate change were often objectified and generally discussed in terms of what might happen to others, rather than to themselves as individuals. The displacement of potential impacts as something that will occur to others, as opposed to self, may be a coping mechanism or a way of resisting change[38,40]. For others, it may simply be that because of their age they have little interest in the impacts of climate change in the future.

Given that participants were drawn from a number of different stakeholder groups and industry sectors, beliefs about the social and economic impacts of climate change are described in relation to each group or sector.

## Commercial and recreational fishing

Several fishers indicated that there was little preparedness amongst the commercial fishing industry and recreational fishing sector to respond to the impacts of climate change. This was because they had been preoccupied with other changes occurring in their industry or sector, including the trawl and reef line plan and the representative areas program. As shown in the following quotation, it could be argued that many in the commercial and recreational fisheries sectors, as a consequence of recent changes, have limited resources and adaptive capacity to respond to climate change issues, signalling a vulnerability to climate change.

> *'I have to say [it] is not top priority on our radar. There are far more important threats to our industry, our leisure and our recreation than climate change.'*

In contrast, several commercial and recreational fishers believed they would adapt to the impacts of climate change because through the recent changes to their industry and sector, they had become more resilient by developing a greater capacity to adapt and respond to future changes.

While it was indicated that the live fish industry may have to change its methods for the storage of live fish given temperature increases, that there may be an increase in costs associated with cooling and refrigeration, and that the use of equipment to measure sea temperature may be more common, the most frequent response amongst both commercial and recreational fishers was that they would adapt their fishing patterns and methods to whatever the prevailing conditions were at the time. However, there was no indication from participants that the commercial and recreational fishing sectors were in any way preparing for the impacts of climate change.

## Tourism

In contrast to fishers, who indicated they were more likely to respond and adapt to change as it occurred, participants from the tourism sector expressed far more concern about the impacts of climate change and indicated a willingness to prepare for any potential climate change impacts.

Of particular concern for many participants from the tourism sector, was the image climate change impacts on the GBR would create amongst potential visitors. For the tourism industry, coral bleaching may not only have a direct impact on the marine tourism experience, but the national and international publicity associated with coral bleaching and the image of the GBR as being 'damaged' by climate change could create a negative image of the GBR and effectively reduce visitor numbers. In this sense, the tourism industry was seen as being potentially vulnerable to negative messages about coral bleaching and the impacts of climate change.

On a somewhat related issue, there was also an emphasis on managing the impacts of climate change and the experience of climate change impacts by visitors, by ensuring that the product that represented the visitor experience of the GBR did not create expectations that were too high. Clearly any mismatch between the expectation of the reef experience and the actual experience itself could also have a significant negative impact on the reef experience by visitors[27].

In relation to reef tourism, several participants indicated the reef experience might become more staged, similar to the 'staged authenticity' of tourism experiences as described by MacCannell[41], with tour operators 'farming' individual sites to ensure a quality experience amongst reef visitors. The farming of reef sites would generally include the employment of specialists to manage sites, which participants suggested would include the maintenance and transplantation of the corals and fish feeding being used to attract the larger and more iconic species of fish. Other potential impacts and changes discussed by the tourism sector included operators relocating to sites with less visual impact and in more extreme cases, a possible shift from reef based tourism to water or ocean based water sports or other similar non-reef based activities. Increases in sea level were also perceived as having a potential impact on tourism infrastructure, particularly in the major coastal ports such as Port Douglas, Cairns and the Whitsunday Islands.

The projected increase in the frequency of intense cyclones was also seen as having a potential impact on the tourism industry. Quite apart from the direct impacts of cyclones on coral reefs and tourism infrastructure, participants indicated two possible issues associated with an increase in the intensity and duration of cyclones. Firstly, there was a belief that increased cyclonic activity may create a significant amount of negative publicity in the international tourism market, resulting in a decline in international visitors. Secondly, climate change may extend the cyclone season by commencing earlier or finishing later, which in itself may reduce the effective tourism season for international visitors.

### Traditional Owners

One of the key areas of concern for Traditional Owners was the impact of increased sea temperatures and potential changes in seasonal patterns on the availability of plant and animal life for traditional uses. In addition, and of concern to several participants from coastal Traditional Owner groups, was the impact climate change may have on their totems[29]. Totems are used to identify Traditional Owner groups and may be represented in any number of marine animals and plants. As totems are an important part of Traditional Owner cultural identity and are especially significant in song and dance, any loss of totem animals or plants would have significant impacts on the cultural identity of Traditional Owners including their lore and kinship relationships.

> *'…we have sea creatures or animals that we know as our totem so we'd rather preserve and look after those animals so that we know that we are connected to the area…lore and our kinship and relationship with other groups within our tribes and neighbouring tribes. If we do lose some of these animals and coral species it would be a big blow for our cultural heritage and our stories.'*

Several Traditional Owners believed climate change would have a significant impact on their communities, resulting in the displacement of people from coastal communities through increase in sea level. Examples were given of islands in the Torres Strait that are currently being affected by rising sea levels, and there was concern about the impacts of moving people in these communities from their home islands and country to other island communities.

While several Traditional Owners identified potential impacts from climate change on themselves and their culture, others accepted that change was inevitable and essentially part of the natural order of their country and had occurred in the past.

> *'I think we will adapt very easily. We don't complain a lot about stuff. We just watch things that happen then we go along with it because that is how we've worked for thousands of years. We just adapt. When one fish dies off and becomes obsolete, we eat the other. And they are all food…and the algae may bring other things around…other food into the area.'*

### Regional NRM organisations

A complex institutional environment deals with issues relating to climate change. Institutional arrangements such as plans and policy initiatives now deal with climate change either exclusively, or as part of addressing a range of NRM issues at national, state, regional and local levels. Key state agencies include the Queensland Environmental Protection Agency, and the Departments of Natural Resources and Water, Primary Industries and Fisheries, and Premier and Cabinet. Key federal agencies include the Department of Environment and Water Resources and the Great Barrier Reef Marine Park Authority. Industry groups and the private sector are also taking an active role in establishing arrangements to manage the uncertainties and risks posed by climate change.

Regional natural resource management organisations also have a responsibility for natural resources in the coastal catchments adjacent to the GBR. These organisations not only address coastal and marine water quality issues, but also a wide range of other critical NRM issues in each catchment. In Queensland, regional NRM organisations have been operational for the past five years and each organisation has developed a regional NRM plan in the last two to three years, which identifies management targets and associated actions they intend to implement to address the critical NRM issues in their region.

Several participants were from regional NRM organisations and while there was recognition and acknowledgement of climate change, the imperative to address climate change issues and the delivery of specific management actions associated with climate change was limited. NRM plans developed by regional NRM bodies will often include an array of several hundred management actions. However, many of the NRM plans did not appear to recognise climate change as a driver for their management actions, nor was it common for management actions to be included in response to climate change. Some regional NRM organisations have a relatively limited response in their plans to climate change.

> *'Within the plan itself…we do have one management action that primarily is focused on climate change…and it is to do some scenarios with Local Government…with the coastal councils for emerging issues.'*
>
> *'…we just started to delve into what the organisation does about that.'*

The lack of urgency in recognising and addressing climate change issues amongst regional NRM organisations appeared to be attributable to two core issues. Firstly, in developing their NRM plans and investment strategies these organisations were required to develop plans and strategies which were community based and which represented the NRM issues of concern to stakeholders and communities in each region[34]. Several years ago, when these plans and strategies were being developed, climate change was not a significant issue for many in the community. As a consequence, climate change issues appear only on the periphery of many NRM plans and it was rare that specific management actions were developed in response to climate change issues. Secondly, regional NRM organisations are locked into a three-year investment cycle for the delivery of their NRM plan and they do not necessarily have security beyond this. The dilemma is that while these organisations have a responsibility at a regional level for the management of natural resources, the short term institutional constraints on their funding and operation makes it exceedingly difficult for them to address longer-term issues associated with climate change. As one participant indicated, the best many regional NRM organisations can do is to improve the resilience of ecological systems in the short term, so that they are better able to absorb and potentially recover from climate change impacts in the future.

## Coastal development and planning

While there was some recognition of the impacts of climate change for coastal development and planning, political and institutional constraints were identified as the key impediments to changes in existing coastal development and planning which would address climate change issues.

Most importantly, these participants identified institutional constraints and barriers as frequently inhibiting their response to climate change. For example, several participants indicated that there clearly should be no development allowed in flood prone or storm surge areas of the coast. However, pressures for increased development of the coastal zone and the significant capital investment being made in coastal regions meant that it was difficult at a political level to resist these development demands. In many instances, agencies found themselves being only able to provide advice or guidelines for new developments or building structures to protect existing developments.

> *'I would be surprised if there's anything we can do about it…they are spending millions of dollars getting the absolute beachfront house and 90 percent of the population's dream is to do that. So the politicians are not going to stop them putting that sort of investment right on the front in the most prone areas. And when it comes to it they'll have enough political clout to get the politicians to see it their way. So I think the coast line in the urban areas will be strongly defended by lots of rock walls, which means the beaches will disappear and we will lose a lot of the values of the coastline.'*

Several participants believed the State was only just obtaining controls over coastal development that were needed to limit liability in relation to storm surge or flood and as such there would be a continued emphasis on the development of engineering solutions, including the building of groynes and sea walls. However, as one participant indicated, the size of the sea walls required to prevent storm surges would most likely *'start blocking people's views…which will become an extremely political issue to manage.'*

While participants recognised there were significant institutional and political issues associated with addressing the impacts of rising sea level on coastal development within existing urban development areas, some participants found that they achieved greater success in relation to development control by focussing on new developments in non-urban areas.

## 23.7 Summary and recommendations

Climate change is driving shifts in environmental conditions that, together with other human pressures, are having synergistic effects on the GBR. Individuals, communities, and industries in the GBRCA depend directly or indirectly on the GBR for ecosystem goods and services. These take the form of direct economic benefits (including commercial activities such as tourism and fishing), social services (including recreational activities and cultural linkages) and environmental services (including shoreline protection from barrier reefs and mangrove stands).

There is limited research and literature assessing the impacts of climate change on communities, industries, and stakeholder vulnerability and resilience in the GBR. Outside the GBR, global climate change literature predominantly explores public understanding of climate change and there is limited literature describing social vulnerabilities to climate change and social responses to climate change. Based on the available social science literature:

- There is a wide variation in people's beliefs or 'mental models' about climate change.
- Measuring community and industry vulnerability to environmental change, such as climate change, is difficult because of the limited availability of useful research and datasets.
- Societies can adapt to climate change at multiple scales through short- and long-term adaptive strategies. The range and extent of both these responses defines the resilience of the community.

The study by Fenton and Beeden[26] of stakeholder beliefs about climate change in the GBR catchment is the only specific social assessment of climate change issues in the GBR. It identified a number of core issues associated with climate change in the GBR catchment.

- There is considerable variation in the recognition and acknowledgement of climate change across the spectrum of stakeholders in the GBR, both in the level of experiential and scientific knowledge about the marine ecosystem and climate change. Some stakeholders have very detailed local knowledge and belief systems about how the ecology of the local area functions. In contrast, much of the knowledge about marine ecosystems and climate change within government agencies and regional NRM organisations is based on 'scientific data' and the knowledge of 'experts'.
- Stakeholder understanding and perceptions of climate change are influenced by a wide range of individual and socio-cultural factors in the GBR. The schemas individuals develop for climate change processes are based on multiple sources of information, both experiential knowledge and 'expert' information. Climate change in the GBR is not conceptualised as a series of independent events, but rather as a series of interdependent and causally connected events occurring within the environment. There is a significant lack of scientific information about climate change, and individuals try to fill the gaps in their knowledge through their own experience and beliefs about climate change.

- Identifying the consequences, impacts or responses to climate change – while there is some commonality across individual cognitive models of the impacts of climate change, there are significant differences in the breadth and depth of knowledge about its potential impacts.

The study found that although climate change is an objective and measurable event, it is understood and acted upon as a subjective event. It is constructed by different stakeholder groups and imbued with meanings derived from experience and the social and cultural context in which individuals, industries and communities find themselves. Individuals, stakeholders and communities' recognition and acknowledgement of climate change, how they construct and give meaning to climate change processes, and the content of their anticipatory schema in relation to climate change impacts and response, essentially determine their vulnerability, adaptive capacity, adaptation, and resilience to climate change. This study clearly shows there is a difference in preparedness amongst different stakeholder groups to climate change impacts.

### 23.7.1 Potential management responses

Climate change presents considerable challenges for management because it involves considerable uncertainty, the potential for irreversible damage or cost, a very long planning horizon, time lag between cause and effect, and the need for systemic institutional change[14].

The implementation of management actions to address climate change is hindered by:

- Institutional complexity, confusion, poor coordination and integration of arrangements. This leads to a poor articulation of desired outcomes and the desired management actions of community and industry stakeholder s to deal with climate change.
- An insufficient overall framework for climate change and no framework for the delivery of programs or incentives.
- Insufficient opportunities for public involvement in developing policy and management responses.

Any management actions developed to increase preparedness for climate change needs to recognise the diversity of constructs used to define climate change and its impacts across different stakeholder groups. A single approach towards preparedness and management is unlikely to have an effective response with all groups therefore management responses need to involve diverse community and industry stakeholders in the process. Furthermore, across the different stakeholder groups, the level and quality of interaction with science 'experts' and the trust that underpins these relationships will need to be recognised and addressed to ensure equity in any management response.

While it is important, through good marine management, to maintain and ensure the natural resilience of marine ecosystems from human induced climate change, there is a question about whether it is equally appropriate to do the same for social systems. If the actions of existing social systems are reducing the resilience of the ecological system by contributing to climate change, then response strategies that build and maintain current behaviour patterns would be counterproductive and maladaptive. In terms of enhancing resilience in social systems, the focus must be on facilitating adaptation and building the adaptive capacity to proactively bring about transformation in the interaction of the social-ecological system. The role of natural resource management in the context of social systems is to increase the capacity of people and communities to recognise, learn and benefit from such change.

The capacity to cope with nonlinearities or other forms of surprise and uncertainty requires openness to learning, an acceptance of the inevitability of change, and the ability to treat interventions as experiments or adaptive management[39]. Rather than focus on the provision of information, policy efforts should address the social and institutional barriers that hinder community and industry, involvement in, and leadership of, efforts to address climate change[15].

### 23.7.2 Further research

More research into the social dimensions of climate change is needed to support institutional processes and management strategies that are appropriate and effective in dealing with climate change given the complex social environment of the GBR. Participatory and deliberative management approaches require a deeper understanding of the diverse stakeholder groups, their experiences, and the social and cultural context in which individuals, industries and communities find themselves.

There is a need for greater knowledge and understanding about community and industry vulnerability to climate change in the GBR, information showing how people and organisations have adapted to change in the past; and research into stakeholder and community attitudes and perspectives on management options that will facilitate effective change processes.

There is a need to combine socioeconomic characteristics that are currently available with more focused social and economic assessments of climate change to understand stakeholder attitudes and perspectives with respect to climate change and participation in management strategies and to understand stakeholder vulnerability, resilience and adaptive capacity to climate change in the GBR.

It is also important that science and the science of the ‘experts’ needs to be integrated with a better understanding of individuals’ local knowledge of climate impacts and the cognitive models they possess of climate change. To maintain separation of these two knowledge systems will restrict our understanding of human response to climate change, impede the urgency of the community and industry action required to address climate change issues, and will maintain amongst some a continued mistrust of science and the organisations and institutions that disperse scientific information.

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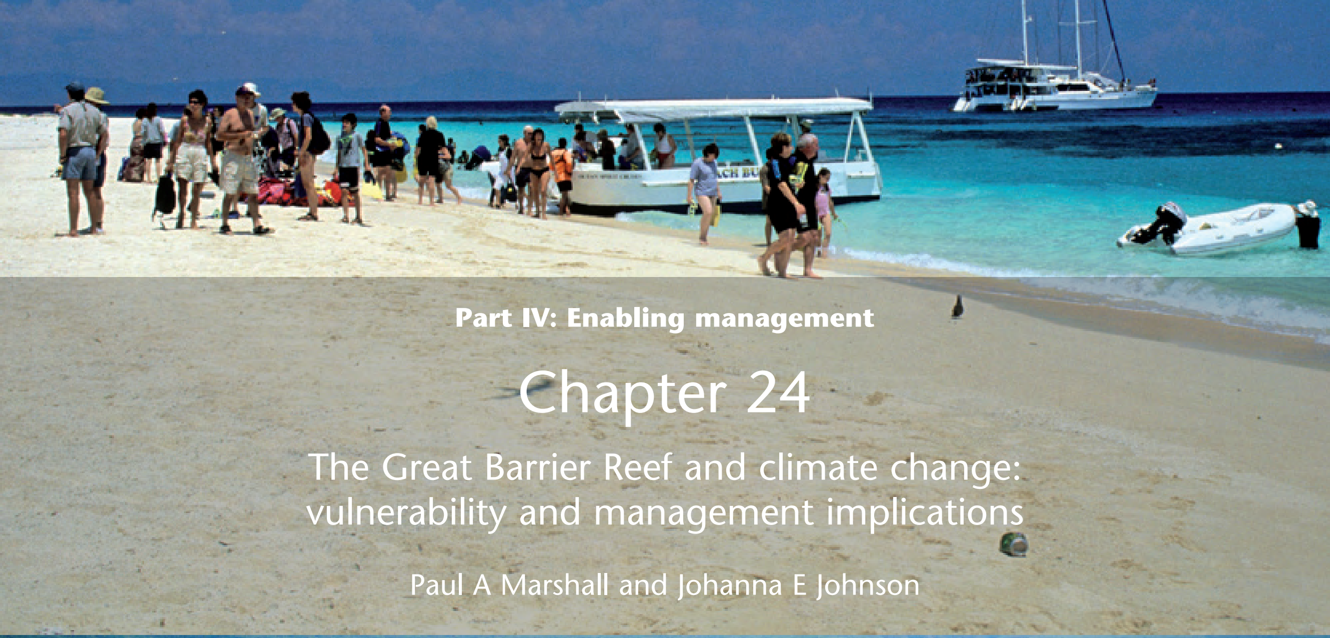


Part IV: Enabling management

# Chapter 24

## The Great Barrier Reef and climate change: vulnerability and management implications

Paul A Marshall and Johanna E Johnson

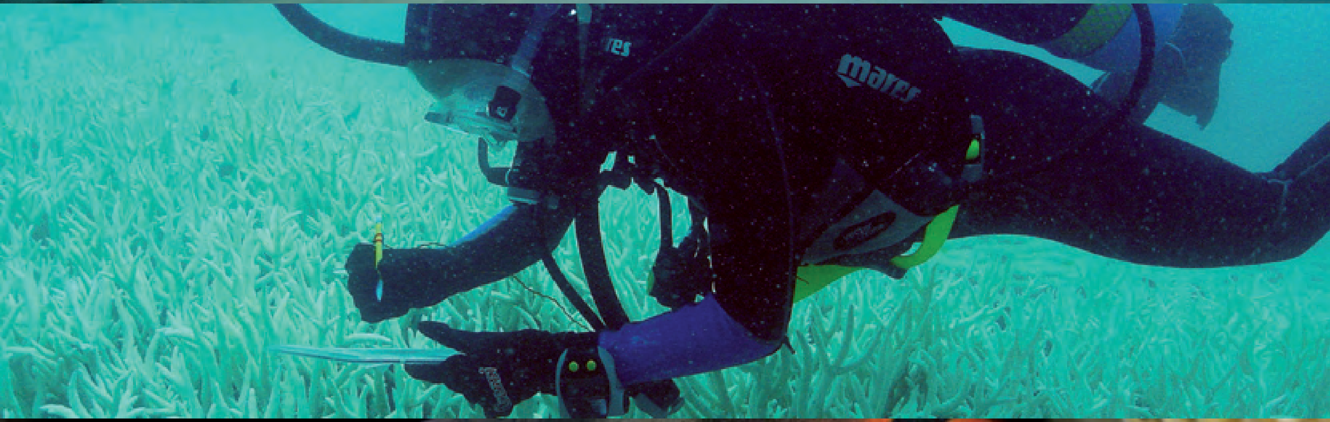


Image courtesy of Triggerfish Images

This book provides an authoritative assessment of climate change vulnerability for the species and habitats that make up the Great Barrier Reef (GBR). The picture that emerges from the combined knowledge of 86 experts is that the GBR is exposed to a range of stressors associated with climate change, and that many components of the GBR (which includes both ecological and human dimensions) are highly sensitive to these stressors. While the GBR is likely to be more resilient to climate change than most tropical marine ecosystems around the world, it is far from immune to this pervasive threat. In fact, signs of vulnerability to climate change are already being observed in critical parts of the GBR ecosystem, such as corals and seabirds. In addition to presenting a synthesis of current and emerging knowledge, the experts who contributed to this assessment provided recommendations for ways to reduce the impacts of climate change on the GBR. These insights provide the foundations on which tropical marine ecosystem managers can build an informed and effective response to climate change.

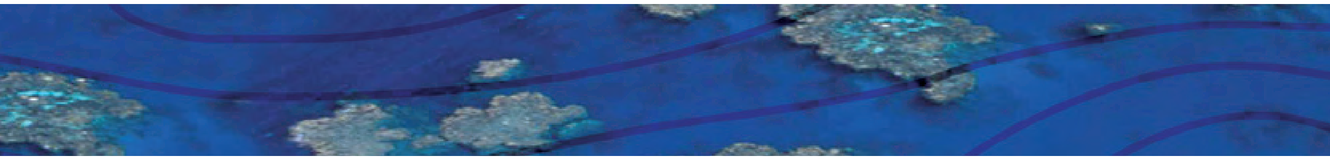
In this chapter, we begin with a synopsis of previous chapters, covering the latest knowledge on exposure, sensitivity and vulnerability of the GBR to climate change. Building on this summary, we synthesise ideas about potential management responses suggested by the contributing experts. The findings of this vulnerability assessment provide a rigorous and comprehensive basis for management planning and policy. The information in this final chapter is provided as a summary of the opinions of scientific experts.

## 24.1 Vulnerability of the Great Barrier Reef to climate change

The combination of sensitivity and exposure to climate change render the GBR ecosystem highly vulnerable to climate change. While the components and processes that comprise the ecosystem vary in their vulnerability, the implications of climate change are far-reaching and, in many cases, severe. Overall, the GBR ecosystem has features that will afford it some protection from climate change compared with tropical marine reef ecosystems. These features include its immense size, its location adjacent to a relatively sparsely populated and developed country, and its protection under a management regime that is recognised as the best in the world[20]. However, coral reefs are one of the most vulnerable of all of the earth's ecosystems to climate change[10], and the GBR will continue to be affected. Even under the most optimistic climate change scenarios, the GBR is destined for significant change over this century; under pessimistic scenarios, catastrophic impacts are possible[2]. In this section, we provide an overview of the exposure of the GBR to climate factors, including a summary of predicted changes to the GBR climate, followed by a review of the reasons for the sensitivity of the GBR to climate change. We then provide a synopsis of current and emerging knowledge about the vulnerability of GBR species groups and habitats to climate change.

### 24.1.1 Exposure of the Great Barrier Reef

Climate change is unlike any disturbance experienced by contemporary coral reefs: it has the potential to simultaneously and severely affect tropical marine ecosystems spanning hundreds and thousands of kilometres. Further, the spatial extent of exposure applies to nearly every climate variable, many of which are projected to change rapidly over the coming century. Changes associated with climate change that have implications for the GBR include increasing air and sea temperatures, ocean acidification, nutrient enrichment (via changes in rainfall regimes), altered light levels, more extreme weather events, changes to ocean circulation and sea level rise.



This vulnerability assessment confirms that increasing sea temperature is the single biggest risk factor for the GBR over the short- to mid-term (years to decades). Sea temperature increases are the major cause of the predicted decline in coral communities over the current century, with flow-on effects through the entire ecosystem. Warming of the GBR will also directly affect other components of the ecosystem, and will be a major source of stress for many marine plants and animals.

Over longer time scales (decades to centuries), ocean acidification is likely to surpass temperature as the environmental variable of most significance to the sustainability of the GBR ecosystem. Ocean acidification is expected to have major impacts on the ability of corals, calcifying algae and some species of plankton, crustaceans and molluscs to form their skeletons and shells. This threatens the persistence of the carbonate structures that define coral reef habitats.

Changes in patterns of ocean circulation are likely to have far-reaching effects, particularly on key processes such as connectivity and productivity. Potential impacts on plankton species are likely to be partly offset by the high functional redundancy in plankton communities, but potential effects on the pelagic environment – especially on the location and extent of primary productivity – are cause for concern.

In contrast, current projections indicate that sea level rise is likely to be a relatively minor issue for most reef species and processes in the short- to mid-term. However, sea level rise will become a major source of vulnerability for several important habitats, including coastal and estuarine environments such as mangroves and wetlands, islands and cays (as well as the species that depend on these habitats) should these projections be revised upwards in light of recent concerns about accelerated melting of major ice sheets.

## 24.1.2 The changing climate of the Great Barrier Reef

Global climate projections have been used in conjunction with regional observations of climate to develop regional (GBR) projections of air temperature, sea temperature and sea level rise that have a high level of confidence. Projections of ocean acidification, in contrast, are based on global models that have limited resolution at the regional scale. Projections for other climate variables, such as ocean circulation, rainfall, storms and tropical cyclones, and El Niño-Southern Oscillation (ENSO) events also have low confidence for regional applications. Major modelling exercises are underway to refine regional climate projections. These programs are likely to significantly increase the resolution and confidence of climate models, at least for some variables. This section summarises current knowledge about the projected changes to air temperature, sea temperature, sea level, ocean chemistry, ENSO and weather events for the GBR region over this century.

### Air temperature

Coastal air temperatures in the GBR region have already warmed and are projected to increase by 1.4 to 5°C (above 1990 temperatures) by 2070[19]. This is significant for habitats exposed to air, such as mangroves, intertidal seagrass and other coastal habitats, as well as islands and cays. Many of the species in these habitats are also sensitive to changes in air temperature, particularly extremes of temperature (eg marine turtles and seabirds).

### Sea temperature

Regional GBR sea temperatures have increased by 0.4°C since 1850 and are projected to increase by a further 1 to 3°C above present temperatures by 2100 (Lough chapter 2). Increases have been greater in the central and southern GBR (0.7°C since 1850) and this pattern is likely to continue into the future. An increase in sea temperature is likely to be the most critical of all changes to the region's climate, having implications for most marine species. Species groups from corals and plankton to fish and seabirds are sensitive to these changes (chapters 5 to 16).

### Sea level and ocean chemistry

Sea level has already risen and by 2020 is projected to increase by 38 to 68 cm (relative to the 1961 to 1990 baseline). Ocean acidity is projected to increase by 0.4 to 0.5 pH units over the same timeframe (Lough chapter 2). Species and habitats in the intertidal zone are particularly vulnerable to sea level rise, including seagrass, mangroves and associated wetlands, coasts, estuaries and islands and marine reptiles (Waycott et al. chapter 8, Lovelock and Ellison chapter 9, Hamann et al. chapter 15, Sheaves et al. chapter 19 and Turner and Batianoff chapter 20).

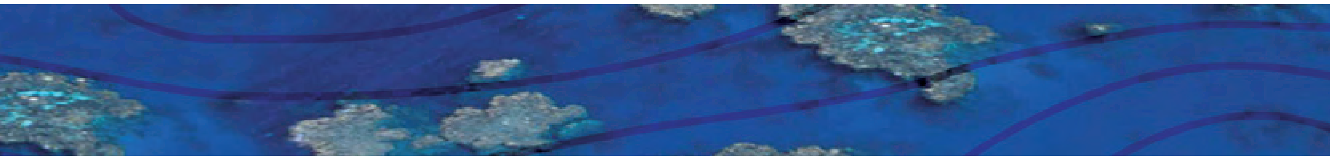
### ENSO and weather events

There is less certainty about changes to ENSO and weather events such as storms and rainfall. However, while the extent of change is difficult to predict, in general the direction of change can be predicted with moderate confidence. Tropical cyclones are projected to become more severe, with a 5 to 12 percent increase in wind speed projected. Variability of rainfall and river flow is expected to increase, resulting in more intense droughts and rainfall events. ENSO will continue to be a source of high inter-annual variability (Lough chapter 2). Changes to ENSO and weather events, although uncertain, will have implications for many parts of the GBR ecosystem.

## 24.1.3 Sensitivity of the Great Barrier Reef

The GBR occurs in a tropical ocean realm where key environmental variables, such as sea temperature, generally fluctuate relatively little over seasonal or diurnal time frames. Typically, the range of sea temperature experienced by tropical marine organisms over the course of a year is substantially less than that experienced by terrestrial organisms in a single day. Further, the huge buffering capacity of the oceans has ensured a highly stable chemical environment for the GBR over time scales of centuries and millennia. As a result, many tropical marine organisms have evolved narrow environmental tolerances, rendering them sensitive to apparently small changes in environmental conditions. This sensitivity has resulted in tropical marine habitats such as coral reefs being extremely vulnerable to climate change relative to most other habitats.

Climate change is driving shifts in environmental conditions that are already beginning to exceed the narrow tolerances of many GBR species and affect key processes. However, there is one feature that distinguishes the GBR ecosystem from most other coral reef ecosystems on the planet: its immense size. Covering 344,400 $km^2$, the GBR Marine Park is immensely complex and heterogeneous in both physical and biological terms. The geographical extent and diversity of habitats act, to some extent, as a safeguard against ecosystem-wide catastrophe. Compared to smaller coral reef ecosystems, the probability of the entire GBR being destroyed by any single disturbance is low. However, while the scale of the GBR acts to reduce sensitivity at the landscape scale, local and regional sensitivity remains high for many species and habitats.



### 24.1.4 Vulnerability of species groups

A significant source of the vulnerability of the GBR is the extensive connectivity within the marine ecosystem. The linkages and inter-dependencies among organisms, and between organisms and processes, mean that impacts on one component of the ecosystem are likely to have consequences for other components. This connectivity is also an important factor in the resilience of the GBR. This assessment has extended our knowledge of the vulnerability of all parts of the ecosystem, from marine microbes and plankton to fishes and seabirds and charismatic mega fauna. While many species groups have intrinsic sensitivities to climate change, there are also groups that will experience indirect effects. These indirect effects result from the linkages and inter-dependencies among organisms, and between organisms and processes. This extensive connectivity, which characterises marine ecosystems, means that impacts on one component of the ecosystem are likely to have flow-on effects for other components. This section summarises the key vulnerabilities – both direct and indirect – identified for the main species groups in the GBR.

#### Marine microbes

Marine microbes are a fundamental part of the GBR ecosystem responsible for nutrient cycling (microbial loop), facilitating benthic larval settlement (eg of coral planulae) and for forming partnerships as part of critical symbiotic relationships. The group also includes pathogenic species responsible for disease in many reef organisms such as hard and soft corals, sponges and some echinoderms. Increasing sea temperature, ocean acidification and nutrient enrichment resulting from changes to rainfall patterns are the climate variables that will pose the greatest threat to marine microbes. Short generation times and functional redundancy mean that, functionally, marine microbes are only moderately vulnerable to climate change impacts, as community composition can shift rapidly in response to changing conditions. However, specialised communities (eg sponge symbionts) and some species (eg thermophiles) are likely to be highly vulnerable to climate change. In contrast, pathogenic microbes are likely to be positively affected by climate change with increased virulence and abundance in warming nutrient rich waters. A change in microbial communities that are important in the microbial loop will have implications for the entire ecosystem, which relies on these communities to alter and liberate bioavailable nutrients that are essential for higher trophic levels. A loss of symbiotic microbes will have serious effects on the benthic organisms that rely on symbioses, with implications for sponges, corals and other benthic invertebrates. An increase in disease incidence will have deleterious impacts on the many benthic organisms that are susceptible to disease, particularly if increased sea temperatures and other climate-related changes have already caused stress. As a fundamental component of the marine ecosystem, changes to marine microbial communities will be critical for most other organisms in the GBR (Webster and Hill chapter 5).

#### Plankton

Plankton are another group that are fundamentally important to marine ecosystems through their roles as the dominant component of pelagic environments (both in terms of biomass and abundance) and as key primary producers. The group is most vulnerable to changes in ocean circulation – critical for plankton distribution and dispersal – and, to a lesser degree, nutrient enrichment through changes to rainfall patterns and upwelling regimes. Increasing sea temperature, ocean acidification and changes to ultraviolet (UV) light may also affect plankton. Due to the short generation times and functional redundancy of plankton, they are able to rapidly respond to environmental change and therefore functionally are only moderately vulnerable to climate change. However, some species (such as the calcifying pteropod Cavolinia sp.) are highly vulnerable to changes in environmental conditions. Changes to the plankton community will have cascading effects on higher trophic levels and are likely to have consequences for most other organisms in the GBR ecosystem (McKinnon et al. chapter 6).

### Macroalgae

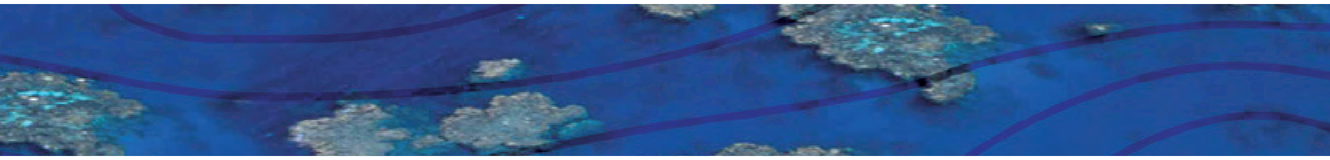
Macroalgae in marine ecosystems have a diverse range of roles including primary production, carbon storage, nitrogen fixation, facilitating larval settlement and reef degradation. Macroalgae are one of the few groups in the GBR that are likely to benefit from climate change through increased nutrient and substrate availability. Increasing sea temperature, ocean acidification, nutrient and carbon dioxide ($CO_2$) enrichment and changes to UV light are the climate changes that will directly affect macroalgae. Turf and upright fleshy macroalgae are unlikely to be negatively impacted by climate change and are likely to benefit through increases in productivity, growth and reproduction. Increases in substrate availability due to increased coral mortality (as a consequence of recurrent bleaching) will promote algal colonisation and increase the area of reef covered by turf and fleshy macroalgae. However, this may cause shifts in competitive balance resulting in shifts in species composition, which would lead to algal assemblages that are markedly different in ecological structure and function. Crustose coralline algae are highly vulnerable to ocean acidification with flow-on negative consequences for coral larval settlement and calcification (reef accretion). Increasing growth and reproduction of turf and fleshy macroalgae will have positive consequences for nutrient cycling. However, competition shifts in benthic habitats will result in reef degradation and algal dominated reefs (Diaz-Pulido et al. chapter 7).

### Seagrass

Seagrass are a diverse component of the GBR ecosystem, inhabiting both intertidal and deepwater environments. Seagrass are significant primary producers and provide habitat and food resources, sediment stabilisation and local biochemical and hydrodynamic modification. These roles are particularly important for maintaining coastal habitats and limiting sediment and nutrient delivery to inshore coral reefs. Seagrass are most at risk from changes to UV light, which is important for photosynthesis and growth of all seagrass species, particularly as a result of increased turbidity from floods and sea level rise. Other climate changes that pose a threat to seagrass are increasing sea temperature, storms and changes to ocean circulation. Nutrient enrichment and increasing atmospheric and oceanic $CO_2$ concentrations will also affect seagrass but are likely to have a positive effect by increasing growth rates. Reductions in UV light and reduced light penetration from pulsed turbidity will affect photosynthetic rates, making seagrass communities moderately vulnerable to climate change. While most species have low vulnerability, *Halophila, Halodule* and *Zostera* are sensitive to reduced light levels associated with increased turbidity. Changes in seagrass communities will have implications for nutrient cycling, availability of critical habitat (eg for juvenile fishes) and food resources (eg for dugong and green turtles), sediment stabilisation and local hydrodynamics (Waycott et al. chapter 8).

### Mangroves

Mangroves are important primary producers that play major roles in cycling and storing nutrients, and providing critical nursery habitat for many species (eg larval and juvenile fish). They also provide biofiltration and coastal stabilisation services, and are a major influence on local biochemical and hydrodynamic environments. Due to their location in the intertidal zone, mangroves will be affected



by sea level rise, particularly if the rate of rise is greater than the vertical accretion rate of mangrove habitats. Reduced rainfall, increased storms, increasing air and sea temperatures, atmospheric chemistry and changes to ocean circulation will also affect mangroves. Overall, mangroves are considered to have moderate to high vulnerability to climate change, depending on the rate of sea level rise. Loss of mangroves and associated tidal wetlands will have implications for higher trophic levels through changes in nutrient cycling, changes to critical nursery habitat, loss of coastal stabilisation and hydrodynamic modification, and for reef organisms, loss of sediment biofiltration and increased nutrient delivery to inshore reefs (Lovelock and Ellison chapter 9).

### Corals

While coral reefs comprise only six percent of the overall area of the GBR Marine Park, corals play a fundamental role in the GBR ecosystem. Corals are the major source of calcium carbonate accretion in the GBR ecosystem, making them indispensable for the building and maintenance of the physical foundations of the entire ecosystem. Shallow reef-building corals are highly sensitive to changes in environmental conditions, in particular increasing sea temperature and ocean acidification. Corals will also be affected by changes to light regimes, more intense storms and flood events and changes to ocean circulation. Due to their sensitivity to environmental variables, corals are highly vulnerable to climate change. The potential for climate change to severely affect corals has already been demonstrated through the two severe mass bleaching events that occurred on the GBR in 1998 and 2002. Loss of corals will have catastrophic consequences for reef structure and for reef habitat that is critical for species of reef fish, benthic invertebrates, marine turtles, sharks and rays. In addition, the potential loss of reef-building corals has implications for the physical structure of the GBR, with serious and lasting impacts for other habitats, as well as for the people and industries that depend on them (Hoegh-Guldberg et al. chapter 10).

### Benthic invertebrates

Benthic invertebrates (other than corals) are a diverse group of organisms that play important roles in biofiltration of seawater and suspended matter (eg sponges), nutrient and carbon cycling, bioerosion (eg polychaetes), provision of habitat (eg sponges and gorgonians), bioturbation, reef building (eg molluscs), detrital recycling (eg crustaceans) and predation (eg crustaceans and molluscs). Many benthic invertebrates are also commercially important for fisheries, such as some species of prawns, crabs, molluscs and sea cucumbers. Although a diverse group, benthic invertebrates share a high sensitivity to increasing sea temperature. Particular species also have a moderate sensitivity to changes to ocean circulation, storm and flood events and ocean chemistry. The high diversity of benthic invertebrate phyla, encompassing a wide range of life histories, means that species range from low vulnerability (eg highly mobile species such as some cephalopods and crustaceans) to moderate vulnerability (eg moderately mobile species such as some gastropods) to high vulnerability (eg sessile species such as sponges and giant clams). Loss of species that are highly vulnerable to climate change will have consequences for reef structure (modified bioerosion), nutrient cycling and reducing biofiltration of sediments and nutrients (Hutchings et al. chapter 11).

### Fishes

Fishes play a critical role in transferring energy through the ecosystem. They fill discrete functional roles, such as high-level predation and algal grazing, that are critical to maintaining ecosystem function. Some species such as coral trout, red-throat emperor, mackerel and snapper, are commercially important.

Fish are sensitive to increasing sea temperature and changes to ocean circulation, both of which are likely to affect population distribution and larval dispersal. Coastal species are also likely to be affected by sea level rise and flood events. The most significant impact on fish from climate change however, is likely to be from modification of habitats that are critical to their life histories, such as coral reefs, mangroves and seagrass meadows. Fish vary in their vulnerability to climate change depending on the climate variable (eg they are more vulnerable to increasing sea temperature than sea level rise) and the habitat occupied (reef-dependent species are more vulnerable than pelagic species). Reduced fish abundance and diversity will have implications for the food web (both higher and lower trophic levels) and for dependent fisheries (Munday et al. chapter 12).

### Sharks and rays

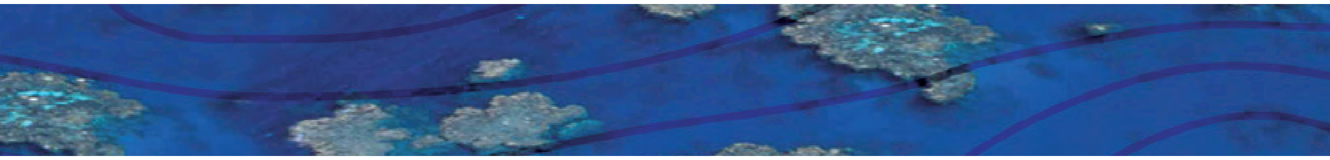
Sharks and rays provide an important functional role as top-level predators within the GBR ecosystem. They are essential for regulating prey species such as fish, molluscs and crustaceans. Many shark species provide substantial social and cultural values, and some are taken in significant numbers by commercial fisheries, either as target species or as bycatch. Sharks and rays will be affected by changes in sea temperature, changes to ocean circulation and freshwater inputs as a result of changing rainfall patterns. The most significant vulnerabilities for this group relate to modification of coastal habitats such as estuaries and mangroves, and disruption of ecological processes that drive productivity and availability of prey through rainfall and oceanographic changes. Of sharks and rays, freshwater and estuarine species are highly vulnerable to climate change impacts and most at risk. Reef species are moderately vulnerable to climate change through the effects of sea temperature and ocean acidification on tropical marine habitats. The implications of this vulnerability will manifest as changes in the food web and at lower trophic levels. Other shark and ray species have low vulnerability to climate change, as they are generalists or mobile. However, this low vulnerability is dependent upon their ability to move and exploit other habitats and resources (Chin and Kyne chapter 13).

### Seabirds

Seabirds are highly visible predators in the GBR ecosystem that are defined by the fact that they feed exclusively at sea. They feed on bait fish aggregations in nearshore, offshore and pelagic surface waters and interact with in-water predators by driving bait fish schools deeper. They also provide a dispersal mechanism for mainland and island plants. Seabirds are highly vulnerable to increasing sea temperature and changes to ocean circulation and ENSO. These climate drivers affect the distribution of warm waters and therefore bait fish aggregations. Seabirds rely on these productivity 'hot spots' for survival and breeding success. Sea level rise also poses a risk to seabirds as some important nesting islands and cays are likely to be inundated. Particularly vulnerable groups include pelagic foraging terns, wedge-tailed shearwaters and many species of boobies. Catastrophic breeding failures and population declines are possible with successive warm years, which will have implications for the wider marine food web, particularly lower trophic levels, and plant seed dispersal. It would also represent a loss of a charismatic component of the GBR ecosystem (Congdon et al. chapter 14).

### Marine reptiles

Marine reptiles, namely turtles, crocodiles and sea snakes, fulfil various ecological roles (from herbivory to top-level predators). Of all marine reptiles in the GBR, turtles are most at risk from climate change. They are particularly sensitive to increasing air and sea temperature (which will affect



hatchling incubation and gender determination) and sea level rise (which may alter the suitability of important nesting beaches). Increased temperatures are likely to have a similar impact on the incubation of estuarine crocodile eggs, but the thresholds are more difficult to determine. Overall, crocodiles and sea snakes are predicted to be only moderately vulnerable to climate change. Likely responses to changed climatic conditions include shifts in the timing of the nesting season and shifts in nesting locations. Changes to the gender ratio of marine reptiles or loss of critical breeding sites – and therefore breeding failure – will have implications in the long-term for populations, and flow-on effects to other trophic levels and the maintenance of cultural traditions of Indigenous Australians (Hamann et al. chapter 15).

#### Marine mammals

Marine mammals of the GBR are an ecologically diverse group and include one species of dugong, 16 species of dolphin and 15 species of whale that are resident or spend part of their life in the GBR. Whales most often inhabit deep-water habitats or migrate from summer feeding grounds in Antarctica to winter breeding grounds in the GBR. Dugongs perform important community and chemical modifications to seagrass habitats, dolphins are top-level predators and whales contribute to nutrient cycling. All marine mammals provide important social and cultural values. The climate drivers that are most likely to affect marine mammals are changes to ocean circulation, storms, flood events and increasing sea temperature. Due to their migratory and mobile nature, marine mammals have only low to moderate vulnerability to climate change within the GBR context. The most significant impacts of climate change on marine mammals are likely to be through their food resources, either through changes in seagrass meadows or the availability of plankton or fish. The sources of these effects extend beyond the GBR, as some marine mammals that frequent the GBR depend upon food resources from other regions, such as Antarctica. Changes to marine mammal populations in the GBR will have some flow-on effects on lower trophic levels (Lawler et al. chapter 16).

### 24.1.5 Vulnerability of habitats

The GBR is substantially more than the sum of its parts. The complex inter-dependencies and links between species and their environment create many recognisable habitats with emergent properties that cannot be attributable to any one species or group of organisms. These habitats normally facilitate the processes and qualities that are both necessary for maintenance and renewal, and essential for the survival of species. Understanding the vulnerability of habitats, in addition to the vulnerability of their composite species, is critical to management of natural resources. This section summarises the key vulnerabilities of the main habitats of the GBR ecosystem as assessed in previous chapters.

#### Coral reefs

Coral reefs are an iconic component of the GBR that, while comprising only six percent of the area of the GBR Marine Park, provide critical habitat and food resources for many species in the ecosystem. The vulnerability of coral reef habitats to climate change is high as the dominant structural components (scleractinian corals) are highly vulnerable to increasing sea temperature and ocean acidification. The increased frequency of coral bleaching that will accompany further increases in sea temperature will cause a decline in coral cover, increases in algal dominance, and shifts to the composition of coral communities towards species that are more thermally tolerant. These species tend also to provide less structural complexity, with implications for habitat services to other species. Loss of live coral and degradation of habitat structure from bleaching will be exacerbated by increased physical disturbance from stronger storms and reduced coral calcification rates (due to ocean acidification). Reduced live coral cover will increase rates of bioerosion and therefore further losses to reef framework. Loss of coral reef habitat will have serious implications for reef-dependent species, and for the physical foundations of the entire GBR ecosystem (Fabricius et al. chapter 17).

### Pelagic environments

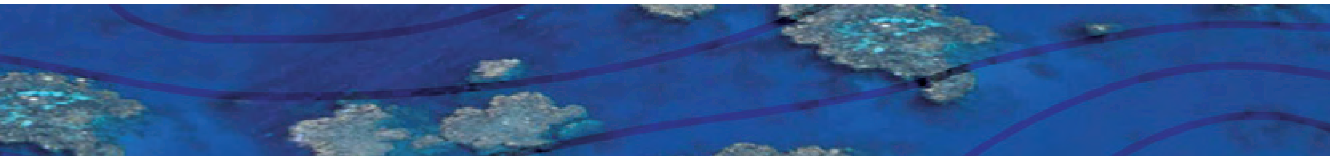
Pelagic environments are important for the transport of propagules (such as eggs and larvae) and food resources. Planktonic assemblages are the basis of pelagic food chains and provide productivity hotspots for higher trophic groups (eg fishes, birds and whales) as well as the larvae and adults of benthic assemblages. Pelagic environments will be most affected by changes to ocean circulation, increasing sea temperature, ocean acidification and changes in ENSO. Their vulnerability is moderate, particularly because of the sensitivity of plankton to environmental changes, and the consequent implications for the productivity of the GBR ecosystem. Plankton communities are major primary producers and productivity on the GBR is strongly influenced by periodic events that alter nutrient availability for plankton, many of which will be affected by climate change. Corresponding changes in the dynamics of plankton communities are expected, with flow-on effects to higher trophic levels. Changes to planktonic communities will affect the pelagic larval stage of many reef-based and other marine organisms. If productivity becomes highly variable, recruitment population dynamics will become more variable, with extreme year classes becoming more common and population replenishment seriously impacted (Kingsford and Welch chapter 18).

### Coastal habitats

Coastal habitats are an important interface between land and sea. They have a critical role in the connectivity of the GBR ecosystem, and provide nutrient cycling, primary production, biofiltration, critical habitat and coastal protection. Coastal habitats comprise estuaries, mangroves, salt marshes, beaches, wetlands, seagrass meadows and nearshore waters and reefs. They are moderately vulnerable to climate change, particularly sea level rise, changes to rainfall regimes and flood events, and increases in sea temperature. Changes to circulation patterns will also affect coastal habitats and have implications for the dynamics of larval supply to reefs and the degree of connectivity between reefs and the coast. Changes to ocean circulation patterns could also interact with changes in temperature and productivity to affect survival of pelagic larvae and condition at settlement. This could lead to impacts on the reproductive success of species dependent on coastal habitats, and affect dispersal of larvae (Sheaves et al. chapter 19).

### Islands and cays

The more than 900 islands and cays form another significant habitat in the GBR, providing key breeding sites for seabirds and marine turtles as well as habitat for many endemic flora and fauna species. Islands and cays are particularly sensitive to sea level rise, changes to ENSO, increasing air temperature and changes to rainfall patterns. Due to their isolation and frequent remoteness, islands and cays are moderately to highly vulnerable to climate change. Implications for the GBR ecosystem include loss of critical habitat and breeding sites, particularly for protected species, and degradation of a unique component of the GBR seascape (Turner and Batianoff chapter 20).



### 24.1.6 Interactions between stressors

Interactions between climate and localised non-climate stressors are expected to create particularly damaging synergies, adding to concerns about climate change. For example, corals exposed to pollutants, turbidity, sedimentation or pathogens have been shown to be more susceptible to bleaching, or less able to survive a bleaching episode. Similarly, reefs that have fewer herbivores due to fishing pressure may recover more slowly after a bleaching event should macroalgae dominate the substrate after significant coral mortality. Furthermore, chronic local stressors – such as poor water quality – can affect the recovery potential of reef communities. This can result because fertilisation and larval recruitment in corals are particularly sensitive to environmental conditions, and because macroalgal growth rates increase in nutrient-rich waters[13]. The effects of elevated temperatures on corals can render them more susceptible to other pressures, for example disease, predation and the cumulative effects of other non-climate stressors. Similar synergies between stressors are likely to affect other species also, highlighting the urgent need to develop an integrated approach to reducing climate change impacts through building ecosystem resilience.

### 24.1.7 Historical perspective

The fossil record provides information on past climate conditions and climate change and how coral reefs responded over geological timeframes. This historical perspective shows that tropical marine ecosystems have experienced climate change of a magnitude comparable to (and in some periods greater than) the IPCC projections in their geological history. However, it also reveals that the *rate of change* expected over coming decades is unprecedented.

Coral reefs have endured throughout the fossil record, despite previous warming events. This highlights the natural resilience of these ecosystems over geological time scales despite large environmental variability (Pandolfi and Greenstein chapter 22). However, there is clear evidence of massive ecological shifts during these climatic changes, with prolonged periods (hundreds of thousands to millions of years) during which there were dramatically altered communities. For example, coral components of reef ecosystems are insignificant during the latter half of the Palaeozoic, with reefs instead dominated by algae that secreted high-magnesium calcite and aragonite skeletons (Pandolfi and Greenstein chapter 22). These dramatic changes and extended periods of recovery provide insights to the potential fate of present-day coral reefs under climate change scenarios.

While the paleoecological evidence suggests that the projected *magnitude* of climate change is not likely to result in the complete extirpation of coral reefs globally or locally, the significance of the projected rate of climate change is more difficult to ascertain. Further, today's coral reefs are exposed to a range of stresses that are unique to the modern era. The impacts of human activities have altered much of the marine environment in which coral reefs occur, undermining the resilience of these ecosystems[2,8]. Together, these factors suggest that *"…modern coral reefs might be much more susceptible to current and future climate change than is suggested by their geologic history"* (Pandolfi and Greenstein chapter 22).

### 24.1.8 Vulnerability of industries and regional communities

The GBR catchment area currently has a population of almost 850,000 people. While most towns and communities in the region have a strong economical dependence on agriculture, manufacturing and mining, several major communities – including Cairns City, Douglas Shire and Whitsunday Shire – depend on tourism as their major industry. Commercial, charter and recreational fishing, and land-based support industries, are other important industries in the region, contributing to the social fabric and economic opportunities in many regional communities. Aboriginal and Torres Strait Islander peoples have a strong presence in the GBR, relying on it for important cultural activities such as fishing, hunting and maintenance of ancestral linkages.

The benefits provided by the GBR to individuals, communities and industries include a range of ecosystem goods and services. These goods and services take the form of direct economic benefits (including commercial activities such as tourism and fishing), social services (including recreational activities and cultural linkages) and environmental services (including shoreline protection from barrier reefs and mangrove stands). Consequently, climate impacts on the GBR ecosystem are expected to be a significant mechanism by which GBR communities and industries are exposed to risks from climate change.

This assessment has found that, as for ecosystem components, the vulnerability of GBR communities and industries is a function of their sensitivity and exposure. Sensitivity is largely a function of the nature and strength of dependencies that regional communities and industries have on the natural resources[16]. Exposure results from changes to the availability of or access to the ecosystem goods and services on which communities and industries depend. In contrast to the ecological components of the GBR however, human communities have the capacity to anticipate change, prepare coping strategies and implement planned adaptation measures. For this reason, one of the most important determinants of vulnerability for communities and industries of the GBR is their adaptive capacity. The extent to which social and economic systems are able to maintain key functions and processes in the face of change – their resilience – is a key indicator of their vulnerability to climate change. The only recent study of coastal communities within the GBR region[5] investigated the likely adaptive capacity of communities and industries to climate change and identified three core issues:

i) Community members vary in their recognition and acknowledgement of climate change

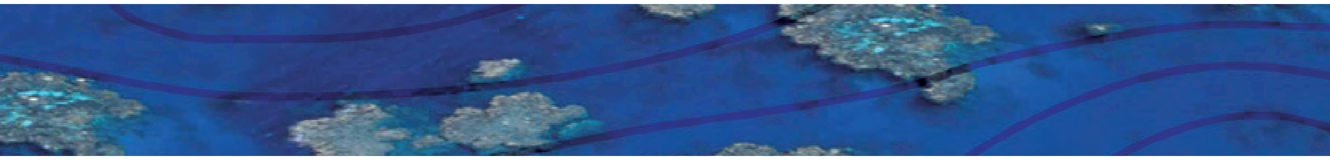
ii) GBR industries vary in their understanding about climate change and climate change processes

iii) Greater awareness about climate change is needed before industries and communities can identify the consequences, impacts or possible responses to climate change

The Fenton and Beeden study found these issues existed for all groups or sectors interviewed: Traditional Owners (Aboriginal people), commercial and recreational fishing, tourism, regional natural resource management organisations, and coastal development and planning.

#### Traditional Owners

For thousands of years, Aboriginal and Torres Strait Islander people have fished, hunted and gathered in the waters, adjacent coastal areas, and on the islands in the area that today we know as the Great Barrier Reef. They relied on these areas for traditional resources and customary practices, and recognise



many important cultural sites and values throughout the GBR. Today there are some 70 Traditional Owner groups along the coast from the Torres Strait to Bundaberg with an interest in, and connection to, coastal land and the GBR. Almost 55,000 Indigenous people live along the GBR coast or within the GBR catchment, which equates to 50 percent of all Indigenous people in Queensland. Access to country (including sea country), maintaining cultural identity, and the continued maintenance of traditional hunting rights for sustainable use of marine resources are three critical issues of current concern to Traditional Owners within the GBR catchment area.

Traditional Owners identified increased air temperature as a major concern associated with climate change. Changing temperatures are likely to alter the seasonality and availability of marine resources on which they depend for traditional hunting and gathering. Other concerns included the potential loss of totem species, such as dugong and marine turtles, and displacement of coastal Traditional Owner communities due to rising sea levels.

These concerns indicate moderate sensitivity and moderate to high exposure to climate change. However there were indications of high adaptive capacity among Traditional Owners. This could stem from their cultural experience with long-term changes, such as sea level rise over their 60,000-year history. Although further work is needed to obtain a reliable measure of resilience, this assessment did reveal among at least some Traditional Owners a pragmatic attitude to change that has the potential to significantly moderate their vulnerability to climate change.

### Tourism

The GBR tourism industry, as part of regional tourism, contributes A$6 billion to the Australian economy through some 20 million visits to the region and over 1.9 million visits to the GBR with commercial operators[1]. There is considerable diversity in the GBR tourism industry, ranging from high speed vessels carrying hundreds of passengers for day trips to large pontoons, through cruise ships, sailing or fishing charters, island resorts and kayak tours.

The tourism industry regularly deals with fluctuating visitation to the GBR while having to contend with changes in the quality of many reef sites due to coral bleaching, poor water quality and the impacts of crown-of-thorns starfish. This direct experience with changes in resource quality, coupled with the strong dependency of many sectors of the tourism industry on high ecosystem quality, render them especially aware of their sensitivity and exposure to climate change impacts. As a result, tourism operators were found to be actively concerned about the impacts of climate change on their businesses and livelihoods, and indicated a willingness to prepare for any potential climate change impacts.

Some of the key sensitivities to climate change identified by the tourism industry[a] include degradation of reef sites due to temperature-induced coral bleaching, poor recovery of degraded sites as a result of other stressors such as water pollution, and deteriorating ocean-going conditions due to increased storm activity. One of the other major concerns for tourism operators was the potential for the GBR to lose its marketing advantage as a high quality reef destination as a result of climate change. Even though other reefs around the world are likely to have similar or even greater vulnerability, the profile given to climate change impacts on the GBR (especially coral bleaching) was seen to impose some

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[a] GBR Marine Tourism Operators Forum on Climate Change, November 2005

level of business risk through its potential impacts on destination appeal, and therefore on market share. In combination, these issues amount to the tourism industry having both high sensitivity and high exposure to the effects of climate change.

Potential impacts from climate change can be expected to be offset, somewhat, by the high adaptive capacity of the tourism industry. The industry's strong awareness of the risks, and early indications of their willingness to identify and pursue strategies of mitigation and adaptation suggests a high level of resilience. Examples of this adaptive capacity include industry investment in understanding the risks from climate change and development of a GBR Tourism and Climate Change Action Strategy[b]. Mitigation strategies that tourism operators are considering include reducing their climate footprint through use of biodiesel fuels, sail or solar power and purchasing carbon offsets for their greenhouse gas emissions. Examples of adaptation strategies that tourism operators are contemplating include revising marketing strategies to ensure they accurately reflect the condition of tourism reefs (to avoid discrepancies between the expectations and actual experience of tourists), active enhancement of tourism sites through maintenance of corals and feeding to attract fish, and relocating operations to less vulnerable sites. The total economic impacts of climate change may be reduced to some extent by substitution effects, such as shifts from reef-based tourism to beach holidays, water sports or other activities that are less dependent on reef quality[1].

### Fishing

There are five main commercial fisheries operating in the GBR that together catch about 24,000 tonnes of seafood each year, and have a total gross value of A$251 million[1]. Recreational fishing is also a major activity. There are estimated to be about 800,000 recreational fishers in Queensland, and those using the GBR contribute about A$623 million to the Australian economy annually[1]. These fishers are estimated to have an annual catch of 3500 to 4500 tonnes.

Fishing, particularly commercial fishing, is highly sensitive to any changes in fish availability or access to fisheries resources that may result from climate change. This vulnerability assessment found that the adaptive capacity of fishers appears to be generally low (Fenton et al. chapter 23). Interviews with fishers indicated that there was little preparedness in the commercial fishing industry and recreational fishing sector to respond to the impacts of climate change. This appears to be in some part due to the recent increase in regulations, which have been implemented to increase the resilience of the GBR ecosystem, and thus safeguard fisheries for the future. Commercial and recreational fishing have been regulated in recent years with the introduction of legislation such as the Fisheries (East Coast Trawl) Management Plan (1999), Fisheries (Coral Reef Fin Fish) Management Plan (2003), new *Environment Protection and Biodiversity Conservation Act* (1999) guidelines and the new Zoning Plan for the GBR (2003). The new Zoning Plan increased highly protected areas (which are closed to fishing) from 4.5 to 33 percent[4]. Consistent with reports on fisheries from other parts of the world, many GBR fishers expressed a strong belief in their adaptive capacity, yet few indicated preparations were being made in anticipation of climate change.

This assessment found that the commercial and recreational fishing sectors were characterised by high sensitivity and moderate to low adaptive capacity. Direct exposure to changes in cyclone and

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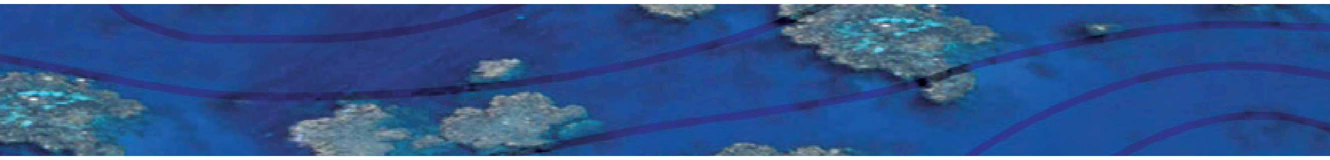
[b] Coordinated by Queensland Tourism Industry Council



storm activity is likely to be an area of concern, affecting access to sites and the number of fishing days. However, a definitive assessment of their vulnerability to climate change is difficult at present due to the large knowledge gaps about exposure. While this assessment has found that many species of fish, including those targeted by fishers, are vulnerable to climate change as a result of increases in sea temperature, changes in ocean circulation and loss of habitat, it was unable to predict the magnitude of these impacts, or the resultant economic impacts. Until quantitative estimates of changes to abundance, size and distribution of target fish species are developed, it will remain difficult to assess the vulnerability of commercial and recreational fishing to climate change. This knowledge gap is also likely to hamper the adaptive capacity of fishers.

### Regional natural resource management

Regional Natural Resource Management (NRM) bodies have an important role in identifying community aspirations for maintaining the natural resources in the coastal catchments of their regions adjacent to the GBR. Queensland NRM organisations have developed regional plans, which identify management targets and associated actions to address critical NRM issues. Many of the plans currently do not incorporate climate change as a driver for their management actions, nor do they commonly include management actions in response to climate change. This may reflect that NRM plans were mostly developed several years ago, when awareness of the importance of climate change to NRM issues was relatively low within the broader community. Clearly, NRM processes will need to take account of climate change issues if they are to respond to the threats that climate change poses to natural resources in the coastal catchments of the GBR.

### Coastal development and planning

Coastal development and planning appear to be highly vulnerable to climate change. Despite widespread recognition of the sensitivity of coastal infrastructure, and its high exposure to sea level rise and increased storm intensity, adaptive capacity appears low at present. Clearly, major vulnerabilities exist, especially if higher sea level rise estimates are correct. This assessment has identified that political and institutional constraints appear to be key impediments to planned adaptation to climate change. Community members and officials involved in coastal issues already cited significant investment (eg infrastructure) in vulnerable coastal areas and limited evidence of decision-makers to limit ongoing coastal development in flood prone or storm surge areas of the coast. The soaring desirability of seaside properties and their commensurate value continues to create powerful incentives for development in the coastal strip, resulting in high – and increasing – vulnerability to climate change.

## 24.2 Potential management responses

This assessment has found that vulnerability of the GBR takes many forms, with climate change predicted to affect species, habitats, processes and human systems in varied ways. Consequently, climate change threatens to undermine or modify the ability of the ecosystem to deliver the goods and services upon which regional communities and industries have come to depend. This not only has implications for those directly affected, but for the government organisations responsible for managing the natural resources.

As the Australian Government agency responsible for planning and management of the GBR, the goal of the Great Barrier Reef Marine Park Authority (GBRMPA) is the *'long-term protection, ecologically sustainable use, understanding and enjoyment of the Great Barrier Reef through the care and development of the GBR Marine Park'*. Recent initiatives to improve water quality and to increase protection of biodiversity were taken to help meet this goal. However, climate change brings a new suite of pressures to the GBR. The global nature of the threat, and its relatively recent emergence, make climate change a serious challenge for marine protected area managers, as well as for the ecosystems in their care.

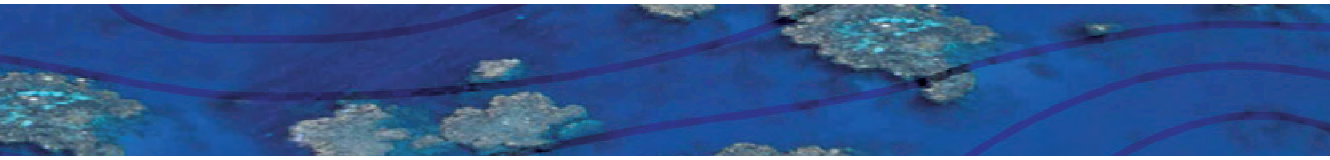
Despite these challenges, marine protected area managers have an important role in addressing the threats posed by climate change. Through partnerships with scientists, communities and industries, management agencies such as the GBRMPA are playing a lead role in efforts to maintain the capacity of tropical marine ecosystems (and the industries and communities that depend on them) to cope with climate change.

The many experts who have compiled the vulnerability assessments in this book also suggested strategies to reduce the vulnerability of key habitats and species groups. This section summarises their recommendations for adapting management of the GBR to climate change, which fall into two broad categories: promoting mitigation and supporting resilience.

### 24.2.1 Mitigation of climate change

Mitigating the rate and extent of climate change is repeatedly identified throughout this vulnerability assessment as a priority issue that must be addressed if the GBR is to cope with climate change. There is no component of the GBR ecosystem that is not sensitive to the effects of climate change, and reducing the amount of change that occurs is the single most effective way of minimising negative impacts. The rate of climate change is also important in determining the scope for adaptation; mitigation helps buy time for adjustments that can reduce the damage caused by climate change[7]. Further, the extent of climate change – the maximum level of stress attained – determines the risk of irreversible damage occurring. If critical thresholds are reached, no amount of investment in resilience can prevent serious damage to certain ecosystem components, the organisms that depend on them and the goods and services that they provide. Mitigation and resilience-building are, therefore, complementary strategies: both are necessary if tropical marine ecosystems are to cope with climate change[15]. Mitigation becomes particularly important for the maintenance of habitat components of the GBR ecosystem, such as coral reefs, pelagic environments, coasts and islands, which have limited capacity to recover should climate change cause particularly serious damage. For these reasons, mitigation is a central issue for the GBR and its management.

Opportunities for marine protected area managers to contribute to mitigation efforts can take a number of forms, centering on communication (information and awareness-raising) and demonstration (taking measures to reduce the climate footprint of activities on the GBR). Management agencies such as the GBRMPA are looked to as authoritative sources of information about the potential impacts of climate change on coral reefs and associated ecosystems. The GBRMPA has played a key role in raising awareness about the vulnerability of the GBR to climate change, and in ensuring a balanced and scientifically robust knowledge base for decision-makers. As this assessment has shown, there is an urgent need for further action on many fronts to reduce the vulnerability of the GBR.



The expert contributions to this assessment unanimously agree that one of the most decisive elements in the future of the GBR is the rate and extent of climate change that eventuates. In this regard, managers have a direct stake in the success of mitigation efforts. Using knowledge about the implications of climate change for tropical marine ecosystems as a basis for setting mitigation targets and communicating mitigation efforts is becoming core business for managers like the GBRMPA. Further, management organisations and their partners have the opportunity to demonstrate a commitment to reducing their own climate footprint in support of more global mitigation efforts. Initiatives to reduce greenhouse gas emissions by reef-dependent industries such as tourism are already underway, and these can inspire others to reduce their climate footprint.

### 24.2.2 Supporting ecological resilience of the Great Barrier Reef

It is inevitable that climate change will continue to cause degradation of the GBR over coming decades. However, this assessment has found that non-climate stressors are exacerbating the effects of climate change for nearly every component of the ecosystem. In many cases, other stressors increase the susceptibility of organisms to climate change. Even where these stressors do not have a synergistic effect with climate change, they have an additive effect. Climate change is likely to bring many populations close to critical thresholds; reductions in the cumulative effects of other sources of stress could be critical in preventing these tipping points from being reached.

Despite being one of the healthiest tropical marine ecosystems in the world, the GBR is under pressure from a variety of human activities. These interact with climate change, often to exacerbate its effects. Key issues in this regard include catchment uses that result in degraded water quality, coastal development and other activities that constrain future adaptation of species and habitats (eg coastal development that acts as a barrier to future landward migration of mangroves as sea level rises). These local pressures act to reduce the resilience of the ecosystem, undermining its ability to cope with climate change.

Many of the management recommendations presented in this assessment accord with well-established principles for supporting resilience of tropical marine ecosystems[18,8] (McCook et al. chapter 4): reduce stress from water pollution, protect biodiversity, protect key functional groups (such as herbivores) and protect refugia. Significantly, however, this assessment increases the justification for key resilience-building strategies through a deeper understanding of the specific actions and benefits that resilience-based management entails. It also identifies strategies for improving the resilience of particular species groups that are vulnerable to climate change.

While many of the management strategies identified in this vulnerability assessment are already being undertaken, the impacts of climate change will increase the urgency to ensure these actions are successful. The following section presents a synthesis of the management recommendations offered by the experts who have contributed to this vulnerability assessment.

#### Reduce stress from poor water quality

Degraded water quality can be one of the most significant impacts on resilience. Toxicants such as pesticides, and high concentrations of nutrients and sediments, all have the potential to acutely stress many tropical marine organisms. Additionally, and perhaps most importantly, these stressors can have chronic impacts, affecting the ability of organisms to cope with the effects of climate change.

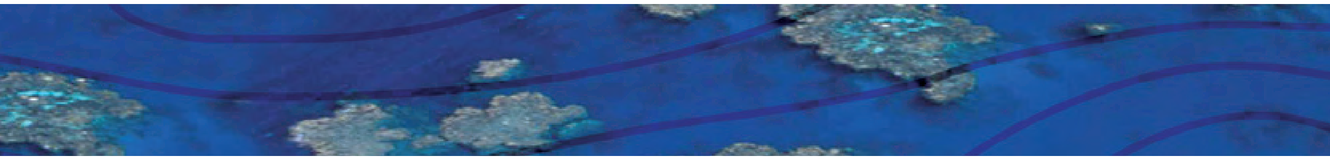
This vulnerability assessment has found that the negative interaction between climate stressors and poor water quality – which in many cases is synergistic – has the potential to seriously undermine the resilience of nearly every component of the GBR ecosystem. For example, the resilience of coral communities is particularly challenged in areas where water quality is degraded, as chronically stressed corals are much less able to recover from bleaching events. Further, coral communities exposed to excess nutrients and sediments have substantially increased recovery times following major mortality events. Improving the quality of water entering the GBR will be a major contribution towards increasing the ability of communities such as corals and seagrass to cope with, and adapt to, climate change.

This assessment has also identified many other plants and animals whose vulnerability to climate change can be reduced through improvements to water quality. Fertilisers and pesticides entering the GBR can have prolonged impacts on plankton communities, seagrass meadows and fish. Microbial communities, which play critical roles in primary productivity, nutrient cycling and facilitation of other key processes like recruitment, are sensitive to nutrients and trace metals, which find their way from the land into the marine environment via freshwater ecosystems. Rivers and localised point sources such as sewage outfalls are sources of toxins and pathogens, which are known to increase the prevalence of diseases in higher animals such as dugong. Reducing levels of particular contaminants that affect microbial communities and increase disease prevalence (such as trace metals and nutrients) can offer a targeted approach to water quality management in the context of climate change.

Climate change is also expected to result in greater intensity of rainfall events, leading to increased risk of erosion and flooding. Efforts to stabilise land areas prone to erosion and investment in strategies to trap sediments and nutrients in the coastal zone (before they enter the marine environment) will become increasingly important in the face of climate change. Toward this end, restoration or protection of mangroves and associated wetlands, and more stringent controls on coastal development, would be a significant contribution to the ability of the GBR ecosystem to cope with climate change.

Improving the quality of water entering the GBR is the goal of the existing Reef Water Quality Protection Plan. The Plan, which is an agreement between the Australian and Queensland governments, aims to halt and reverse the decline in water quality in the GBR by reducing inputs of diffuse sources of pollution and improving catchment capacity to capture and filter pollutants before they enter the GBR. This includes identifying water quality targets for key contaminants through regional NRM plans. These targets and management responses are being developed by the respective regional NRM bodies and will need to reflect the current awareness of the significance and pervasiveness of the effects of climate change. This assessment makes it clear that improvements to water quality are now more important than ever for the future health of the GBR. The emergence of climate change as a dominant threat to the GBR, and the significance of synergies between climate stressors and water quality, highlights the importance of efforts to halt and reverse the decline in the quality of water entering the GBR lagoon.

This vulnerability assessment also provides the foundations for more targeted responses to water quality issues. Not all aspects of water quality interact similarly with climate change, and the significance of interactions varies in space. An urgent priority for management-oriented research is an analysis of the relative importance of different aspects of water quality in determining the vulnerability of key species to climate change. An integrated and spatially explicit understanding of the resilience of the GBR



to climate change would assist managers to prioritise investment of limited resources to maximise the resilience outcomes for the GBR (such as through targeted water quality improvements). This integration is limited primarily by a lack of information on what pollutant loads are being delivered to different parts of the GBR in the context of high-value and high-risk environments. There is a need to incorporate water quality discharge information into current hydrodynamic and receiving-water models.

### Protect key functional groups

A consistent finding of this vulnerability assessment is that the GBR ecosystem will be subjected to increasingly frequent and severe stressful impacts. As a result, the ability of populations, species and communities to recover from damage will become critical for the future of the GBR. Recovery processes are frequently highly sensitive to disturbance, highlighting the importance of identifying and protecting the functions that are essential for recovery. One function that has frequently been highlighted as of central importance to the resilience of tropical marine ecosystems is herbivory. In both observational and experimental studies[8,9,13], herbivores have been shown to be one of the most important functional groups for maintenance of coral-dominated reef ecosystems globally.

In the GBR, herbivores are not currently fished on commercial scales. Measures to ensure the ongoing protection of populations of herbivorous fish in the GBR are in place. Current commercial gear and methods used on reefs (eg line) are not suitable for catching herbivorous fish and there are restrictions on the use of methods that target reef herbivores in commercial scales (eg net). The capacity for future growth of a commercial scale herbivore fishery in the GBR is limited, and consideration of the important role of herbivorous fishes in climate change resilience should be included in future examinations of fisheries legislation and ecosystem-based management approaches.

While the importance of herbivory to the functioning of the GBR ecosystem has been a focus of research in recent years, many other species groups are also likely to play an important role in resilience. Although less studied, higher trophic species, such as sharks, rays, other predatory fishes, seabirds and marine mammals, exert important top-down controls on trophic systems. These predators selectively remove individuals from prey populations that are less well adapted to their environment. Without this selective pressure, it is possible that many lower-trophic species will take longer to adapt to changes in conditions associated with climate change. Therefore, measures to avoid overfishing of demersal predators (such as coral trout and emperors), pelagic species (such as tunas and mackerels) and sharks are likely to play a significant role in maintaining the resilience of tropical marine ecosystems.

Management regimes already exist for fisheries in the GBR. Fisheries across Australia are gradually aligning with the national standards for ecosystem-based management, via mandatory three to five year assessments under the *Environment Protection and Biodiversity Conservation Act* (1999). The first round of assessments have been completed for all GBR fisheries, resulting in acknowledgement that substantial improvements have already occurred but some recommended actions, while agreed to, are yet to be implemented. While climate change concerns were not the driver for this process, these national standards represent a significant tool for maintaining ecosystem resilience. Climate change gives added importance to the timely implementation of ecosystem-based fisheries management plus other important strategies, such as industry led stewardship initiatives.

### Protect refugia

One of the greatest virtues of the GBR in the context of climate change is its immense size and complexity. The expanse and diversity of the ecosystem helps ensure that there is a high level of response diversity, even to global stressors like climate change[8] (McCook et al. chapter 4). The size and complexity of the ecosystem means that there is a high chance that some areas will remain undamaged, or at least will survive in a good enough condition that they are able to act as a source of recovery for areas damaged by climate change. These refugia may be protected from the full impacts of climate change due to physical conditions (such as proximity to upwelling of cooler water or exposure to strong currents), biological qualities (such as a community dominated by bleaching resistant corals) or they might be fortunate by being located in an area that receives lower levels of climate-related stress[15]. Whatever the basis for their resilience, these sites are highly important to the ability of the ecosystem to sustain itself in the face of climate change.

The experts who contributed to this vulnerability assessment highlighted the importance of identifying potential climate change refugia within the GBR, and of ensuring their protection from other stressors. As the effects of climate change manifest themselves through degradation of the GBR over coming decades however, these refugia will also become focal points for industries and other users seeking high quality reef locations. The concentration of use (including tourism, commercial fishing and recreational use) has the potential to substantially increase the risk of local impacts to these areas, compromising their role as climate change refugia. Effective management of marine protected areas under a changing climate will increasingly involve careful monitoring and control of use of activities that otherwise might threaten these refugia[15].

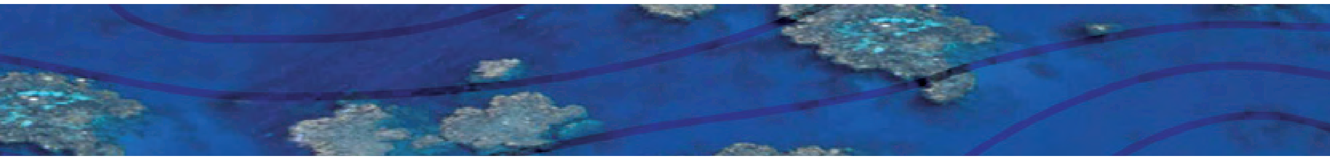
The current zoning plan for the GBR protects representative examples of 20 percent or more of each of the 70 identified bioregions from all extractive uses (including fishing), protecting approximately 33 percent of the GBR Marine Park in total. These areas have been identified by a rigorous process using the best available scientific information. However, the overlap of these highly protected areas with the location of climate change refugia cannot be taken for granted, and should be a focus of future research effort and zoning reviews.

### Restore resilience of particular species groups

This vulnerability assessment has identified a number of opportunities for reducing the vulnerability of particular components of the ecosystem. The recurrent recommendation from the experts contributing to this assessment is that the best chance for minimising the impacts of climate change is through measures to reduce other stressors. Here we synthesise the strategies recommended by authors for supporting the resilience of particularly vulnerable components of the ecosystem: marine turtles, seabirds, fish species, marine mammals, seagrass meadows, islands and coastal habitats.

#### *Marine turtles*

The GBR is an important habitat for marine turtles, and all six species found in the GBR face serious conservation threats at the global scale. While at evolutionary time scales climate change is not a new threat, the combination of climate driven impacts and existing anthropogenic pressures will increase the long-term risk to these iconic reptiles. Increasing air temperatures have the potential to bias the gender ratio of marine turtle hatchlings, while sea level rise threatens traditional nesting beaches.



This assessment has concluded that the effects of increased air temperatures and sea level rise on turtle nests, coupled with human-induced changes in patterns of sand deposition and erosion, and encroachment of human settlements, limit the availability of alternative nesting beaches for marine turtles. Strategies that maximise long-term nesting success – such as planning for shifts in turtle nesting beaches or timing of breeding seasons, reducing beach erosion, removing feral predators and maintaining current and future 'turtle friendly' beaches – will help maximise the adaptive capacity of turtles in the context of climate change. If beach sand temperatures increase to levels consistently above the lethal threshold for embryo development, the viability of turtle populations may depend upon strategies to restore or protect critical habitats (eg increasing shading at nesting beaches, relocating nests to cooler zones or limiting other disturbances). These issues highlight the importance of building climate change considerations into management regimes for coastal areas, including processes for assessing proposed coastal development projects and other activities that might reduce the adaptation options for nesting marine turtles.

### *Seabirds*

The islands and waters of the GBR provide nesting and foraging sites that are critical for many species of seabirds. However, climate change will compromise the ability of the GBR to sustain local populations and measures need to be taken to minimise non-climate stressors at nesting sites and foraging grounds. This assessment identified a number of strategies that should be explored to help protect the ability of seabirds to adapt to climate change. Island management plans that acknowledge the potential for shifts in the timing or duration of bird breeding seasons can facilitate control of human activities that impose additional stress on nesting birds. Birds may also need to shift to alternative breeding sites in order to adapt to climate change, and efforts to identify and protect current and potential future nesting sites will support the resilience of seabirds. Other strategies to increase resilience include maintaining or restoring site qualities that promote nesting success (such as ground-cover or beach profiles). Similarly, measures to address the risk of provisioning failure could also reduce the vulnerability of seabirds to climate change. Such measures might include review of stock assessment priorities and fisheries management measures to ensure fish forage resources (especially bait fish) and pelagic predatory fish (such as tunas and mackerels, which play an important role in making bait fish accessible to foraging seabirds) are adequately protected during unusually warm summers.

### *Fishes*

While many species of fish are vulnerable to climate change, either through direct or indirect effects, the greatest potential for reducing vulnerability through management actions lies with those species that are commercially and recreationally fished. The expert assessment of vulnerability of fish to climate change identified the potential for catch levels that are thought to be currently sustainable to become unsustainable in the future as environmental conditions change. For many species, especially sharks, there is inadequate information for determining population status, let alone sustainable catch levels. Better understanding of current population sizes through improved stock assessments is an urgent priority for many fishery species. However, even current levels of knowledge about climate change vulnerability (and the information gaps) have the potential to improve the long-term sustainability of fisheries if incorporated into fisheries assessments and management plans.

The experts contributing to this vulnerability assessment universally highlighted the existence and significance of knowledge gaps relating to climate change. For this reason, many contributors recommended a management approach that is risk-based, precautionary and adaptive to changing conditions and knowledge. The situation relating to sharks and rays (minimal information about population status but confidence in assessment of high vulnerability) highlights the importance of making allowances for knowledge gaps. Further, efforts to minimise destruction of important habitats (particularly coastal and estuarine nursery areas) and incidental mortality (such as in beach protection and fishery bycatch) will complement fishery-based strategies. Measures that protect known and potential predator diversity hotspots from fishing pressures, particularly those in the pelagic environment, were recommended for building the resilience of predator populations to climate change.

### *Marine mammals*

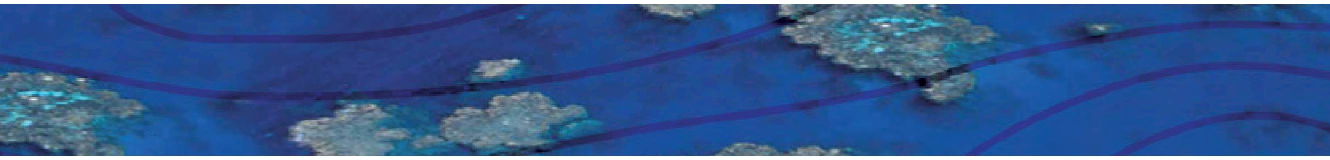
The GBR supports more than 30 species of marine mammals, some of which are threatened with extinction globally. While all marine mammals are already protected by a number of international treaties and laws within GBR waters, they remain under a range of stressors that act to exacerbate their vulnerability to climate change. This assessment has identified a number of non-climate stressors that affect marine mammals, including net entanglement, displacement from feeding areas, boat strike, marine debris, tourism and Indigenous hunting. Most of these stressors are already the focus of management initiatives. However, the emergence of climate change and associated additional stressors increases the imperative for measures to increase protection of marine mammals. Additionally, many of the main food resources for mammals (seagrass, plankton and fish) are also vulnerable to climate change. Strategies that protect the food resources of marine mammals will be important to their ability to cope with climate change.

### *Seagrass meadows*

Dugong and other species that depend on seagrass meadows are vulnerable to climate change due to the sensitivity of seagrass to climate change. Many seagrass meadows are already subject to stressors associated with coastal development and changed sediment regimes, and climate change is expected to increase their vulnerability. Measures that reduce the amount of sediment deposition and turbidity (maximise light penetration) are likely to be influential in reducing the vulnerability of important seagrass habitats, especially in coastal areas. Land management and coastal development plans that support these measures are likely to be important for the long-term sustainability of seagrass meadows. This will be particularly important for species like dugong, as populations along the urban coast are already less than five percent of what they were 40 years ago and declines in seagrass could have catastrophic consequences. Although less is known about inshore dolphin populations, their dependence on seagrass meadows also makes maintenance of this habitat critical.

### *Island and coastal habitats*

Key issues for island management that will become more critical as a result of climate change are weed infestation, pest and disease outbreaks, fire regimes, storm surge, erosion, dredging and other development activities. Island management plans that explicitly consider the changing risk profile for these threats will help reduce the vulnerability of island ecosystems to climate change.



Mainland coastal habitats share many of the vulnerabilities to climate change with islands of the GBR. While terrestrial ecosystems have not been included in this vulnerability assessment, management of coastal habitats will play an important role in the vulnerability of the GBR to climate change because of connectivity within the ecosystem. In particular, important coastal habitats such as mangroves and salt marshes are highly vulnerable to sea level rise and changes in weather patterns. The sustainability of these habitats will depend in a large part on their ability to migrate landward as conditions change, yet increasingly there are barriers to such movement. Similarly, coastal developments, agriculture and other infrastructure projects limit the movement of more mobile species (such as fish) within and between coastal habitats. Removal of coastal barriers, and acquisition or rehabilitation of coastal lands are likely to become important to the future of coastal habitats. Management strategies that protect existing intact coastal habitats, remove and prevent further barriers being established, and reinstate adaptation options will become increasingly important to the management and conservation of coastal ecosystems.

#### *Protected species*

Species such as whales, dolphins, dugongs and marine turtles are listed as threatened or protected by international, national or state legislation and treaties. Some species of seabird are also listed under international treaties such as the Japan-Australia Migratory Bird Agreement and the China-Australia Migratory Bird Agreement. These intergovernmental processes are based on set criteria to assess threats to species. While there are few species for which there is quantitative data on the threat of climate change, the processes are sufficiently flexible to allow consideration of climate change threats if they can be quantitatively demonstrated. The experts who contributed to this assessment highlighted the value of including climate change considerations in intergovernmental processes that aim to protect and conserve these species in the context of climate change.

### 24.2.3 Facilitating social and economic resilience

Changes to the GBR ecosystem will inevitably affect the communities and industries that depend on it. Coastal communities from Bundaberg to the tip of Cape York and the Torres Strait are dependent on the GBR as a major source of income and lifestyle. Industries such as marine tourism and fisheries (recreational, commercial and charter) rely on a healthy ecosystem and the goods and services it provides. Coastal communities also rely on the GBR for recreational opportunities, and for indirect benefits such as coastal protection. The magnitude of the impacts of climate change will depend in large part on the resilience of these communities and industries to the effects of climate change.

One of the most critical aspects of resilience in social systems is adaptive capacity. Resilient social systems have the ability to learn and adapt[6,17], and resilient people and communities recognise, learn and even benefit from the new possibilities that change brings. Regional communities and industries are affected by a multitude of factors operating at multiple scales in time and space. While climate change imposes discrete pressures on people who depend on the GBR in some way, its effects are mediated by the interactions they have with society, economy and the environment. Understanding the social and economic conditions, and regulatory environment, in which people operate can help understand their capacity to adapt to challenges such as climate change. Initiatives to address factors that undermine the adaptive capacity of social systems will increase the resilience of GBR industries and communities to the impacts of climate change.

This section summarises the findings of the contributing experts in relation to the main barriers to adaptation, and presents their recommendations on the potential strategies for decreasing socio-economic vulnerability by facilitating the adaptive capacity of social systems.

### *Coastal communities*

An important observation of this vulnerability assessment relates to the way individuals distance climate change issues. Fenton and Beeden[5] found that there was widespread awareness of the potential for climate change to cause social and economic impacts. The concern, however, seemed to be directed at a community or industry level: community members tended to objectify climate change as a third-party issue, rather than as one that required their personal response. This may be a mechanism for coping with the threat or for resisting change[11,12], or it may reflect a belief that the major impacts will not manifest in their lifetime. More accessible information about potential impacts and opportunities for personal action, presented in a more compelling way, may help remove barriers to behavioural change.

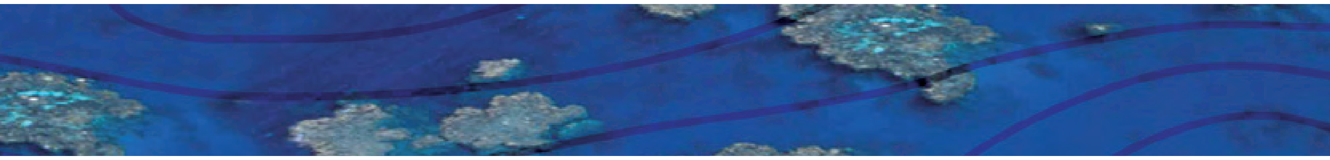
When considered at a broader systems level, climate change has the potential to cause economic and social instability throughout the GBR region. Changes to reef condition, weather patterns and coastal hazards are expected to drive changes in the structure and viability of industries, the demographic characteristics of communities and the adequacy of key social infrastructure such as health care and sanitation[3]. Formal and informal institutions will need to adapt to these changing conditions, preferably in a proactive manner if many of the worst social and economic impacts are to be avoided. Effective partnerships and coordination of efforts across government agencies and non-government organisations will become increasingly important if coastal communities are to successfully adapt to climate change.

### *Traditional Owners*

Traditional Owners have the longest association of any people with the GBR, and an extensive understanding of climate. This knowledge can provide insights into future change as well as temper the potential vulnerability of Traditional Owners through their cultural links with land and sea. Traditional Owners and their relationship with sea country in the GBR are subject to a multitude of pressures, potentially increasing their sensitivity to social and cultural impacts from climate change. Strong partnerships between government and Traditional Owners will help identify potential strategies for minimising the impacts of climate change on the relationship between Traditional Owners and their sea country.

### *Tourism*

The GBR tourism industry is highly sensitive to the changes in resource quality and accessibility (due to weather conditions) that are predicted to result from climate change. At the same time, the industry appears to have good potential for adapting, which may offset some of the effects of climate change. However, a certain degree of economic impact from climate change is unavoidable. The extent of impact will depend, in part, on the nature and size of barriers to industry adaptation, such as market limitations, regulatory controls and financial constraints. Management arrangements that allow flexibility for tourism operators to adapt to change will become increasingly important to industry sustainability. However, social and environmental tradeoffs may need to be made in the GBR in response to climate change, as not all adaptation options that suit the tourism industry are



compatible with ecological resilience or existing management policies. Close partnerships between managers and tourism operators will be used to identify strategies that facilitate adaptation by the tourism sector while also maximising the resilience of the GBR ecosystem.

Site-based interventions are another type of adaptation strategy being considered by reef-based industries. Although not to be considered as ecosystem management strategies, these types of intervention strategies may prove to have a role in helping sustain reef-based businesses in the face of climate change. For this reason, the GBRMPA is supporting efforts by leading tourism operators to develop and test site-based interventions, including strategies to reduce the severity of coral bleaching that occurs at small, high-value tourism sites. Tourism operators have also begun to consider the possibility of enhancing recruitment of corals at degraded sites. However, critical issues of genetic and ecological compatibility, and of economic and logistical feasibility, need to be resolved before such strategies can be implemented. Intensive reef enhancement or maintenance strategies face numerous challenges – not least of which are cost effectiveness and success rates – and they are not likely to be applicable at scales that can contribute to ecosystem resilience.

#### *Fishing*

One of the major issues for commercial and recreational fishing in the context of climate change is the limited knowledge about the vulnerability of most of the fisheries. This stems, largely, from a paucity of data on the magnitude of change likely to occur to important fish stocks. Given this assessment found fishing industries to be sensitive to climate change, with relatively low capacity for adaptation (at least at present), there is a need for better estimates of exposure to climate change. Partnerships between fisheries managers and stakeholders will enable the development of indices for vulnerable fisheries, using the best available information. This will assist with assessing the direction and magnitude of climate-induced change to stocks of important species. This knowledge can then be used to underpin the development of adaptation strategies that will increase the resilience of fishing industries to climate change. Partnerships between management and various fishing sectors will be important for the adaptation of fisheries and developing best practice approaches that will contribute to ecosystem resilience.

## 24.3 Policy responses to climate change

Climate change and its effects on social and natural systems are now mainstream issues receiving priority attention in international and national policy settings. Coral reef ecosystems are recognised as among the most sensitive of the earth's ecosystems, but they are also seen as important indicators of change, and a valuable focus for exploring and testing management responses to climate change. The emerging prominence of tropical marine ecosystems in climate change science and policy circles has led to calls for action from a diversity of arenas.

### 24.3.1 The international call to action

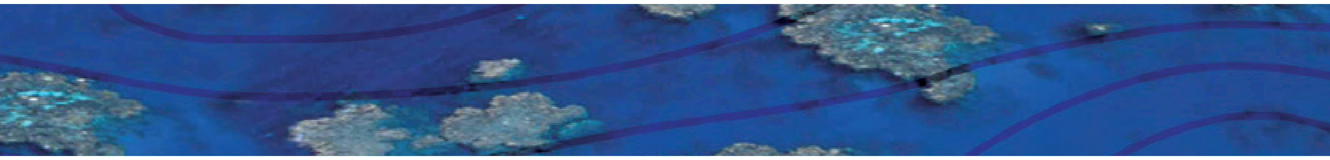
Through the International Coral Reef Initiative (ICRI), four important policy statements have called for international action in relation to mass coral bleaching events and climate change. In 1995, ICRI issued a 'Call to Action' that identified 'the potential adverse effects of climate change' as one of four key threats to coral reefs. Three years later, the worldwide impacts of the 1997–1998 mass coral bleaching event had further heightened concerns about the seriousness of climate change as a threat to coral reefs. This was reflected in the 'Statement on Coral Bleaching' issued at the International Tropical Marine Ecosystem Management Symposium (ITMEMS), a four-yearly summit meeting sponsored by ICRI. By 2003, the international coral reef community had recognised the need and ability to manage for mass coral bleaching. The concluding statement of ITMEMS 2 was 'coral reefs of the world have been deteriorating from coral bleaching and mortality due to warming seas' and that managers can 'address these trends by adopting a number of risk management strategies'. This trend – of moving from a call for research to a call for management – continues with the release of the Action Statement at ITMEMS3, held in late 2006. The statement, endorsed by 324 of the world's leading tropical ecosystem scientists and managers, from 45 countries, concludes that 'climate change is now recognised as one of the most serious long term threats to the biodiversity and services provided by tropical marine ecosystems'. Significantly, it also states that 'managers can take action to reduce the impacts of climate change in tropical marine ecosystems' (see box).

The Convention on Biological Diversity (CBD) has also called for management, research, capacity building and financing of activities that address climate change and its impacts on coral reefs. The CBD has catalysed national efforts to consider climate change-related impacts on biodiversity. In 1998, the CBD formed a Subsidiary Body on Scientific, Technical and Technological Advice, which developed a Specific Work Plan on Coral Bleaching. At the 2004 CBD Conference of Parties, this work plan was updated with a category for 'Management Actions and Strategies' on coral bleaching.

Recommendations relating to climate change in:
ACTION STATEMENT
from the
THIRD INTERNATIONAL TROPICAL MARINE ECOSYSTEMS MANAGEMENT SYMPOSIUM
Cozumel, Mexico
20 October 2006

ITMEMS3 recommends that:

- Managers should promote action to limit climate change to ensure that further increases in sea temperature are limited to 2°C above pre-industrial levels and ocean carbonate ion concentrations do not fall below 200 micomol per kg
- Management planning must incorporate recognition that mass coral bleaching, will have the potential for similar social and economic consequences as other environmental disasters such as droughts, oil spills and other disasters, and will require similar responses
- Facilitate and finance actions to increase resilience of coral reef social-ecological systems, particularly through marine management area networks comprising adequate areas of coral reefs and associated habitats in non-extraction zones, protection of water quality and herbivore populations, and adaptive governance
- Facilitate and finance the development and implementation of coral bleaching response programs, including contingency funding
- Increase investments in targeted messages to accelerate adaptation to climate change
- Invest in village-to-global education and communication for climate adaptation that will integrate traditional and scientific knowledge into implementation of adaptation strategies for coral reefs around the world.



Building on these resilience efforts, the GBRMPA, in partnership with the Australian Greenhouse Office, established the GBR Climate Change Response Program. Established in December 2004, this A$2 million program has been at the forefront of endeavours to understand the implications of climate change for tropical marine ecosystems and to develop management responses. One output of this program is *A Reef Manager's Guide to Coral Bleaching*[14], which was produced in conjunction with the US National Oceanic and Atmospheric Administration to assist coral reef managers worldwide to adapt to the issues relating to climate change impacts.

Communication and engagement with community and industry is a key priority for the GBRMPA, which has built strong partnerships with major stakeholder groups in the GBR region. These have lead to the formation of a GBR Tourism Climate Change Action Group and the drafting of a GBR Tourism and Climate Change Action Strategy. Despite these successes, there are indications of persistent confusion among stakeholders about the implications of climate change. This highlights the value of a strategic and consistent approach to communicating the impacts, implications and current and future management responses to climate change with stakeholders and the broader community.

This vulnerability assessment represents an important milestone in Australia's climate change response. It is the most comprehensive assessment of climate change vulnerability conducted for a tropical marine ecosystem and provides the basis for a continued management response to the implications of climate change for the GBR. As such, it will be an important source document for another major Australian Government initiative that will contribute to future policy responses to climate change – the new *Outlook Report for the Great Barrier Reef Region*. The Outlook Report will provide a regular and reliable means of assessing performance for the long-term protection of the GBR Marine Park. The report will assess the overall condition of the GBR ecosystem, and current and future trends in pressures on the GBR, such as climate change.

### 24.3.3 Climate change and World Heritage listing

The GBR was listed as a World Heritage Area under the World Heritage Convention in 1981. In 2005, a number of non-government organisations put forward petitions to have four World Heritage properties, including the GBR, included on the World Heritage in Danger List because of the threat of climate change to the World Heritage values. At the World Heritage Committee meeting in 2006, the Committee noted but did not adopt the petitions.

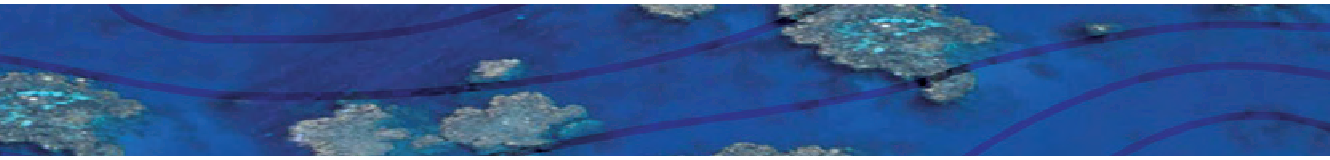
The Committee has so far chosen not to consider the 'in-danger' listing because of climate change but is instead exploring alternative options for addressing this global issue. The Committee has tasked the World Heritage Centre to prepare a policy document exploring issues relating to the Convention and climate change, including alternative mechanisms for 'in-danger' listing.

Australia's efforts to respond to the threat of climate change to the GBR are among the most comprehensive worldwide. Few other World Heritage Areas in the world are doing as much to understand and address the challenges climate change poses. The Australian Government position is that including the GBR on the World Heritage in Danger List will do little to improve the outlook for this World Heritage Area regarding the threat of climate change.

### 24.3.4 Adapting Great Barrier Reef management

The ability of management to adapt to climate change will be critical to the future of the GBR, and for the social and economic services it provides. While science is providing important insights about the impacts of climate change on ecosystems such as the GBR, effective management strategies in a changing climate are only just emerging. There is now a need to test and refine these ideas, and to accelerate learning through sharing management experiences – successes and failures – in responding to the challenges of climate change. The GBRMPA has a key role to play in this global effort, as it is one of the leaders in adapting natural area management to climate change. However, now more than ever before, management needs to address cumulative impacts and be inclusive, bold and adaptive if it is to be effective in averting the crisis that is currently confronting tropical marine ecosystems.

An overwhelming conclusion of this assessment is that key components of the GBR are highly vulnerable to climate change, and signs of this vulnerability are already evident. The range of possible climate futures makes it clear that further degradation of the ecosystem is unavoidable. Even if the causes of global climate change were addressed today, residual greenhouse gases in the atmosphere will prevent the global climate from stabilising this century. Therefore, some degree of change is inevitable. However, the extent of that change, and the implications for the condition of the GBR, will depend on the rate and magnitude of climate change and the resilience of the ecosystem. Even though preventing damage is no longer an option, it is critical that marine protected area managers focus on opportunities for improving the prognosis of this exceptionally important ecosystem. This assessment provides the foundation for such measures in the GBR.



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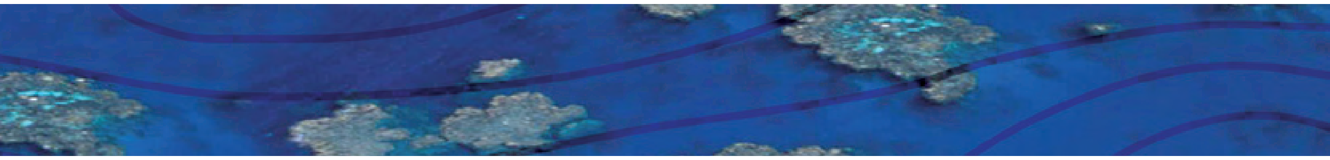


# Glossary of Terms

**acclimation** changes in tolerance under laboratory or other experimental conditions, generally over the short term

**acclimatisation** phenotypic changes by an organism to stresses in the natural environment that result in the re-adjustment of the organism's tolerance levels

**adaptation** an adjustment that moderates harm or exploits beneficial opportunities in natural or human systems in response to actual or expected climatic changes or their effects. A 'biological adaptation' is a phenotypic variant that results in highest fitness among a specific set of variants in a given environment; it occurs when the more vulnerable members of a population are eliminated by an environmental stress, leaving the more tolerant organisms to reproduce and recruit to available habitat

**adaptive capacity** the potential for a species or system to adapt to climate change (including changes in variability and extremes) so as to maximise fitness; moderate potential damages; or take advantage of opportunities, such as increased space availability

**amphidromic** a point within a tidal range where the tidal range is almost zero

**arboreal** relating to or resembling a tree

**Argo** global array of free-drifting profiling floats measuring temperature and salinity of the ocean

**arthropods** characterised by a segmented body, chitinous exoskeleton, paired, jointed limbs and in the class Crustacea

**assemblage** multiple species of plants and animals living in the same place and time

**Atlantic meridional overturning circulation** carries warm surface waters into far-northern latitudes and returns cold deep waters south across the Equator. Its heat transport makes a substantial contribution to the moderate climate of maritime and continental Europe, and any slowdown in the overturning circulation would have profound implications for climate

**attribution** the process of establishing cause and effect with some defined level of confidence

**autotrophs** produce sugars that are essential to consumers, in the pelagic environment, this is usually through photosynthesis (see *phytoplankton*). Autotrophs are the foundation of marine food chains

**azooxanthellate** organisms that do not contain microscopic single-celled algae called *zooxanthellae*, which are commonly found in soft and hard corals

**biodiversity** the number and relative abundance of different genes (genetic diversity), species, and ecosystems (biological communities) in a particular area

**bioturbation** the displacement and mixing of sediment layers by benthic plants and animals

**bottom-up control** refers to ecosystems in which the nutrient supply, productivity, and type of primary producers (plants and phytoplankton) control the ecosystem structure

**broadcast spawning** the simultaneous release of sperm and eggs into the water column. Many species of corals, fish and benthic invertebrates exhibit synchronised spawning in order to increase the chances of fertilization and maximise genetic diversity

**Cephalopoda** means 'head foot' and refers to a class of marine molluscs with well-developed senses and large brains, for example squid and octopi

**chronostratigraphic** a graphic display, with geologic time along the vertical axis and distance along the horizontal axis, to demonstrate the relative ages and geographic extent of *strata* in a given location (also known as a Wheeler diagram)

**climate** the 'average weather', or more rigorously, the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands of years. The classical period is 30 years, as defined by the World Meteorological Organization. These quantities are most often surface variables such as temperature, precipitation, and wind

**climate change** a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods (United Nations Framework Convention on Climate Change) (see *climate variability*). The concept of increased emissions over time and gradual changes in climate is well accepted. Importantly though, fossil evidence clearly demonstrates that the Earth's climate can shift within a decade, establishing new patterns that can persist for decades to centuries. Climate change, therefore, can refer to either a gradual or abrupt change in climatic conditions

**climate variability** variations in the mean state and other statistics of the climate (such as standard deviations and the occurrence of extremes) on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability) (see also *climate change*)

**CLIVAR** a program run by the World Climate Research Program that works to describe and understand the physical processes responsible for climate variability and predictability on seasonal, interannual, decadal, and centennial time-scales, through the collection and analysis of observations and the development and application of models of the coupled climate system

**connectivity** natural links among reefs and neighbouring habitats, especially seagrass beds, mangroves and back-reef lagoons that provide dispersal and genetic replenishment. Also refers to linkages among coastal lands and adjacent catchments, which are sources of freshwater, sediments and pollutants. The mechanisms include ocean currents, terrestrial runoff and watercourses, larval dispersal, spawning patterns, and movements of adult fishes and other animals. Connectivity is an important process to ensure the productive function of the plant and animal species that contribute to the overall health of an ecosystem

**copepod** small pelagic crustaceans (0.3 to 5 mm long) that are important consumers of phytoplankton and some zooplankton, and form an important food source for higher trophic levels

**coral bleaching** the paling of corals and other animals with *zooxanthellae* resulting from a loss of these symbiotic algae. Bleaching occurs in response to physiological shock due primarily to periods of increased water temperature coincident with high levels of light (see *mass coral bleaching*). Bleaching can also be caused by changes in salinity or turbidity

**Coriolis effect** the apparent deflection of objects from a straight path when the objects are viewed from a rotating frame of reference. The best example is the deflection of winds moving along the surface of the Earth to the right of the direction of travel in the Northern Hemisphere and to the left in the Southern Hemisphere. This effect is caused by the rotation of the Earth and is responsible for the direction of the rotation of tropical storms and cyclones

**cryptofauna** animals that are difficult to see when making cursory observations of a habitat. They are usually small and in most cases, highly dependent on their habitats for shelter and food. In the marine environment, these are *demersal* animals

**demersal** dwelling at or near the bottom of a body of water

**detection** the process of demonstrating that an observed change is significantly different (in a statistical sense) than can be explained by natural variability

**East Australian Current (EAC)** a current that originates in the Coral Sea and flows southward along the east coast of Australia

**echinoderms** radially symmetrical invertebrates of the phylum Echinodermata that have an internal calcareous skeleton and are often covered with spines, for example starfish and sea cucumbers

**ecosystem** a community of organisms, interacting with one another and the environment in which they live. Such a system includes all abiotic components such as mineral ions, organic compounds, and the climatic regime

**ectotherm** having a body temperature that varies with the temperature of the surrounding environment

**Effective Juvenile Habitats (EJH)** habitats that have a greater than average overall contribution to adult populations

**Ekman transport** process by which each layer of water in the ocean drags with it the layer beneath. Thus, the movement of each layer of water is affected by the movement of the layer above

**emissions scenario** scenarios describing how greenhouse gas emissions could progress between 2000 and 2100, depending on various hypotheses about human societies and behaviour. As there are an infinite number of possibilities to describe future emissions, scenarios are necessarily conventional with each reflecting a plausible state of the future world. The IPCC has published 40 scenarios grouped into four types (A1, A2, B1, B2) with each representing a different evolution of humanity and associated rates of energy consumption and food production

**endemic** native to or confined to a certain geographical region

**endogeneous** originating or produced from within an organism, tissue or cell

**enhanced greenhouse effect** increasing concentrations of greenhouse gases in the atmosphere trap more heat and raise the Earth's surface temperature

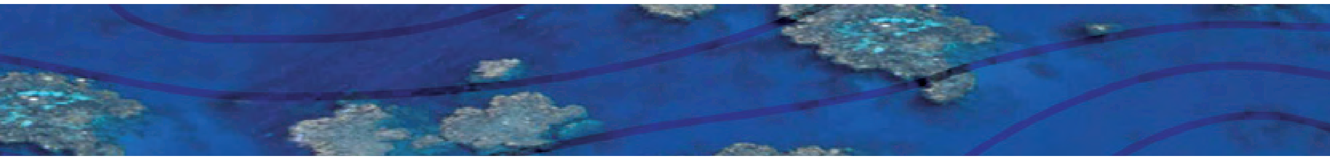
**El Niño-Southern Oscillation (ENSO)** widespread two to seven year oscillations in atmospheric pressure, ocean temperatures and rainfall associated with El Niño (the warming of the oceans in the equatorial eastern and central Pacific) and its opposite, La Niña. Over much of Australia, La Niña brings above average rain, and El Niño brings drought. A common measure of ENSO is the Southern Oscillation Index (SOI), which is the normalised mean sea level pressure difference between Tahiti and Darwin. The SOI is positive during La Niña events and negative during El Niño events

**euphotic zone** the depth of water that is exposed to sufficient sunlight for photosynthesis to occur

**eutrophic** nutrient-rich waters

**eutrophication** the increase in dissolved nutrients and decrease in dissolved oxygen in a (usually shallow) body of water, caused by either natural processes or pollution

**exogeneous** derived or developed outside the body; to originate externally



**exposure** the nature and degree to which a system or species is exposed to significant climate variations. In a climate change context, it captures the important weather events and patterns that affect the system. Exposure represents the background climate conditions against which a system or species operates, and any changes in those conditions

**fissiparous** reproducing by biological fission, a process in which the organism breaks into parts

**genotype** the genetic makeup, as distinguished from the physical appearance, of an organism or a group of organisms

**geostrophic current** the current that results from the forces associated with horizontal changes in density being compensated by accelerations arising from fluid motion on a rotating Earth

**global temperature** usually referring to the surface temperature, this is an area-weighted average of temperatures recorded at ground- and sea-surface-based observation sites around the globe, supplemented by satellite-based or model-based records in remote regions

**global warming** an increase in global average surface temperature due to natural or anthropogenic *climate change*

**gravity wave** in fluid dynamics these waves can be generated in a fluid medium or at the interface between two mediums (eg the atmosphere and ocean) and have the restoring force of gravity, which often results in the wave oscillating around an equilibrium

**Great Barrier Reef (GBR)** tropical marine ecosystem on the northeast coast of Australia that comprises of reef, seagrass, inter-reef, pelagic, shoals and mangrove habitats and includes the islands, cays and coastal areas that are connected physically and biologically

**greenhouse gases** any of the atmospheric gases that contribute to the greenhouse effect. Naturally occurring greenhouse gases include water vapour, carbon dioxide, methane, nitrous oxide and ozone. Certain human activities, such as the burning of fossil fuels, add to the concentration of these naturally occurring gases in the atmosphere

**greenhouse effect** greenhouse gases that are present naturally in the Earth's atmosphere trap heat from the sun to maintain the Earth's surface temperature at a habitable level

**heterotrophs** consumers that cannot synthesise their food and must consume other plants or animals, for example zooplankton and nekton

**impacts** the adverse effect resulting from a threat acting on a vulnerability. Can be described in terms of loss or degradation of any, or a combination of any, ecological, social or economic features

**insolation** a measure of incoming solar radiation incident on a unit horizontal surface at a specific level

**Intergovernmental Panel on Climate Change (IPCC)** an organisation set up in 1988 by the World Meteorological Organization and the United Nations Environment Program to advise governments on the latest science of climate change, its impacts and possible adaptation and mitigation. It involves panels of climate and other relevant experts who assess climate change-related information and prepare reports, which are then critically reviewed by researchers and governments from member countries around the world

**iteroparous** to produce offspring across multiple seasons or years

**larval phase** the early developmental life phase of an animal that is usually different to its adult form. In the marine environment, larvae are often pelagic. In the case of benthic organisms, settlement to the bottom marks the end of this phase (other terms include pre-settlement phase and pelagic larval duration). For pelagic species, growth into a juvenile is the end of the larval phase

**latent heat** the heat released or absorbed per unit mass by a system in a reversible isobaric-isothermal change of phase. In tropical oceanography, the latent heat of evaporation (or condensation) is of importance

**lecithotropic** describing larvae that do not feed during their planktonic phase but rather derive nutrition from yolk

**longwave radiation** heat radiation with wavelengths greater than 4 micrometres (infra-red)

**Madden-Julian Oscillation (MJO)** an atmospheric cycle characterised by the eastward movement of large regions of both enhanced and suppressed tropical rainfall, observed mainly over the Indian Ocean and Pacific Ocean. Cycles last between 30 to 60 days.

**marine snow** a continuous shower of mostly organic detritus falling from the upper layers of the water column, including dead or dying animals and plants, faecal matter, sand, soot and other inorganic dust. As sunlight cannot reach them, deep-sea organisms rely heavily on marine snow as a source of energy

**mass coral bleaching** coral bleaching extending over large areas (often affecting reef systems spanning tens to hundreds of kilometres) as a result of anomalously high water temperatures (see also *coral bleaching*)

**mesograzers** organisms able to use individual seaweeds as both habitat and food. Mesograzers can acquire enemy-free space by inhabiting and consuming seaweeds that are chemically defended against larger, more mobile consumers.

**mitigation** mitigation of climate change refers to those responses that reduce the sources of greenhouse gas emissions into the atmosphere or enhance their sinks. Targets are usually set with respect to a baseline scenario, thus avoiding exceeding the adaptive capacity of natural systems and human societies

**molluscs** a phylum in which organisms are characterised by a shell-secreting organ, the mantle, and a radula, a food-rasping organ located in the forward area of the mouth

**Morphoedaphic Index (MEI)** the total dissolved solids in mg/litre divided by mean depth in metres. The MEI was first developed by Richard A. Ryder in the mid-1960s as an estimator of potential fish yield in lakes, and can be used to predict both fish harvest and standing crop

**nekton** aquatic organisms that are self-propelled (ie not at the whim of the currents) and are large consumers that include squid, fishes, turtles and whales

**neogastropods** an order of gastropods that contains the most highly developed snails whereby respiration is performed by means of ctenidia, the nervous system is concentrated, an operculum is present, and the sexes are separate

**nutrient-phytoplankton-zooplankton models** models that describe the relative interactions of nutrients, phytoplankton and zooplankton in an environment. These can range in complexity, depending on the environment in question, and/or the focus of the research

**octocorals** commonly called ‘soft corals’, they are not close relatives of the Scleractinia, or ‘hard corals’ that have hexaradial symmetry. Octocorals have eightfold radial symmetry, and are made up of colonial polyps, which, in some, perform specialised functions. Excepting the ‘blue coral’ and ‘organ-pipe’ corals, few produce substantial calcium carbonate skeletons while some produce calcified holdfast structures

**oligotrophic** nutrient-poor waters

**ontogenetic** the origin and development of an individual organism from embryo to adult

**osmoregulation** maintenance of an optimal, constant fluid pressure in the body of a living organism

**oviparous** to produce eggs that hatch outside the body

**Pacific Decadal Oscillation (PDO)** a long-lived El Nino like climate pattern with the same spatial implications for climate but lasting from 20 to 30 years rather than the six to 18 months seen in the *El-Niño-Southern Oscillation*

**panmictic** random mating within a breeding population

**pelagic** living in open water (from plankton to whales)

**phenology** the scientific study of periodic/seasonal biological phenomena, such as flowering, breeding and migration, as they relate to climate conditions

**phenotype** the observable physical or biochemical characteristics of an organism, as determined by both genetic makeup and environmental influences

**phenotypic plasticity** the ability of an organism with a given genetic makeup to change its *phenotype* in response to changes in the environment

**photoinhibition** reduction in photosynthetic capacity following damage to the light-harvesting reactions of the photosynthetic apparatus caused by excess light energy

**photoprotection** the use of compounds to minimise the harmful effects of excess light energy

**photorespiration** oxidation of carbohydrates in plants with the release of carbon dioxide during photosynthesis, which lowers the efficiency of photosynthesis

**photosensitise** to make an organism, cell or substance sensitive to light

**photosynthesis** the process in which plants, and some bacteria and protists convert sunlight energy, carbon dioxide and water into sugars and starch. It is a highly complex process beginning with the capture of sunlight by the green pigment chlorophyll and the release of oxygen from water

**photosynthetically active radiation** the spectral range of solar light from 400 to 700 nanometres that is used in the process of *photosynthesis*. Light energy at shorter wavelengths tends to be so energetic that it can damage cells and tissues, though most are filtered out by the ozone layer. Light energy at longer wavelengths does not carry enough energy to allow photosynthesis to take place

**phytoplankton** plant plankton that require light to photosynthesise; they are essential to higher trophic level consumers, such as zooplankton

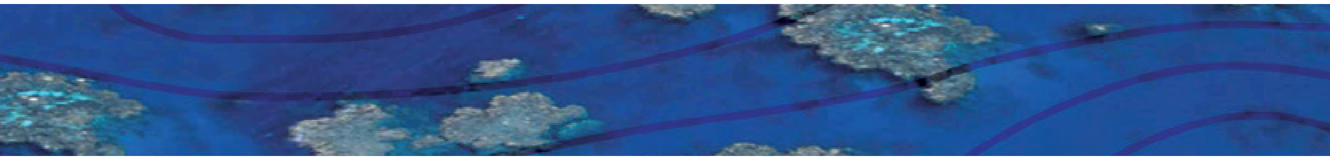
**plankton** all organisms that are considered ‘wanders’ or ‘drifters’. Plankton includes viruses, autotrophs and heterotrophs, phytoplankton and zooplankton

**planktotrophic** larvae that feed on plankton

**pneumatophores** erect roots in swamp dwelling plants such mangroves that are an extension of the underground root system. Since these roots are exposed at least part of the day to the air and not submerged underwater, the root system can obtain oxygen in an otherwise anaerobic substrate, for example mangrove sediments

**poikilothermic** having a body temperature that varies with the temperature of the surrounding environment (eg a fish or reptile); an *ectotherm*

**polyplacophorans** refers to chitons, an order of molluscs distinguished by an elliptical body with a dorsal shell comprised of eight overlapping calcareous plates



**prediction** a statement that something will happen in the future, based on known conditions at the time the prediction is made, and assumptions as to the physical or other processes that will lead to change. Since present conditions are often not known precisely, and the processes affecting the future are not perfectly understood, such predictions are seldom certain, and are often best expressed as probabilities

**primary productivity** rate at which light energy is used by producers to form organic substances that become food for consumers

**projection** a set of future conditions, or consequences, derived on the basis of explicit assumptions, such as scenarios. Even for a given scenario or set of assumptions, projections introduce further uncertainties due to the use of inexact rules or 'models' connecting the scenario conditions to the projected outcomes

**radiation** emission or transfer of energy in the form of electromagnetic waves

**refuges** place where species and/or communities survive environmental changes. Species may remain restricted to the vicinity of a refuge or disperse from a refuge thus recolonising wider areas following further environmental changes. Past refuges might include places where species have survived glacial periods

**resilience** the ability of system to absorb shocks, resist phase shifts and regenerate and reorganise so as to maintain key functions and processes without collapsing into a qualitatively different state that is controlled by a different set of processes

**risk** probability that a situation will produce harm under specified conditions. It is a combination of two factors the probability that an adverse event will occur; and the consequences of the adverse event. Risk encompasses impacts on human and natural systems, and arises from exposure and hazard. Hazard is determined by whether a particular situation or event has the potential to cause harmful effects

**sea surface temperature** the temperature of ocean water at the surface. In practical terms, this will vary depending on the method of measurement used. Infrared radiometers attached to orbiting satellites typically measure the temperature in the top ten microns of the water column while drifting or moored buoys take temperature readings from the top 1 metre

**scaphopods** predatory molluscs with a tubular and, generally, curved shell having openings at both ends

**scenario** a coherent, internally consistent and plausible description of a possible future state of the climate. Similarly, an emissions scenario is a possible storyline regarding future emissions of greenhouse gases. Scenarios are used to investigate the potential impacts of climate change; emissions scenarios serve as input to climate models

**schema** the organization of experience in the mind or brain that includes a particular organised way of perceiving and responding to situations and stimuli

**sensible heat** the heat absorbed or transmitted by a substance during a change of temperature which is not accompanied by a change of state. Used in contrast to latent heat

**sensitivity** the degree to which a system is affected, either adversely or beneficially, by climate related stimuli, including average climate characteristics, climate variability and the frequency and magnitude of extremes

**sensu** (in *sensu stricto*) in a narrow or strict sense

**shortwave radiation** radiation in the visible and near-visible portions of the electromagnetic spectrum (roughly 0.4 to 4.0 micrometres in wavelength)

**sink reefs** reefs that receive larvae via ocean currents. Some reefs may be sinks at one time of year and sources at another time, where monsoonal currents reverse in different seasons

**social-ecological** collective term for the natural and human components of the Great Barrier Reef; that is, the ecosystem and the industries and communities that interact with it

**socioeconomic** the study of the relationship between economic activity and social life. This is a multidisciplinary field using theories and methods from sociology, economics, history, and psychology

**source reefs** reefs the have the potential to supply larvae to other reefs via ocean currents. Some reefs may be sinks at one time of year and sources at another time, where monsoonal currents reverse in different seasons

**Southern Annular Mode (SAM)** a ring of climate variability that encircles the South Pole and extends out to New Zealand, and involves alternating changes in wind and storm activity

**Southern Equatorial Current (SEC)** a broad, westward flowing current that extends from the surface to a nominal depth of 100 metres. Its northern boundary is usually near 4° N, while the southern boundary is usually found between 15 and 25° S

**Southwest Pacific Circulation and Climate Experiment (SPICE)** a multi-organisational experiment working to observe, model and understand the role of the southwest Pacific ocean circulation in the large-scale, low-frequency modulation of climate from the Tasman Sea to the equator, as well as the generation of local climate signatures

**spermatogenic** formation and development of spermatozoa by meiosis and spermiogenesis

**spongin** a sulfur-containing protein related to keratin that forms the skeletal structure of certain classes of sponges

**Stomatopoda** an order of crustacean containing four families of narrow and elongate-bodied mantis shrimps

**strata** a bed or layer of rock or soil with internally consistent characteristics that distinguishes it from contiguous layers

**sublittoral** lying between the low tide line and the landward edge of the continental shelf

**superspecies** a grouping of very closely related species with common ancestry that have developed into true species due to their geographical location

**sustainability** activities that meet the needs of the present without having a negative impact on future generations. A concept associated with sustainability is triple bottom line accounting, taking into account environmental, social and economic costs

**teleconnection** linkage between changes in atmospheric circulation occurring in widely separated parts of the globe

**terrigenous** of or derived from the land and often used to describe sediments that enter the marine environment by erosive action

**thalassinideans** a group of thin-shelled decapod crustaceans that live in burrows in the muddy bottoms of the world's oceans

**thermocline** the region of transition between the warmer surface waters and colder deep oceanic water

**thermoregulation** maintaining a constant internal body temperature independent of the surrounding environmental temperature

**threshold** any level in a natural or *socioeconomic* system beyond which a defined or marked change occurs. Gradual climate change may force a system beyond such a threshold. Biophysical thresholds represent a distinct change in conditions, such as the drying of a wetland. Climatic thresholds include frost, snow and monsoon onset. Ecological thresholds include breeding events, local to global extinction or the removal of specific conditions for survival

**top-down control** biomass at different levels of the food chain is controlled from the top, for example fisheries take fish that consume zooplankton, this allows the abundance of phytoplankton to increase (see *bottom-up control*)

**trophic focusing** the biomass of organisms is aggregated in certain regions of abrupt topography (eg a seamount). It generally results in biomass (and diversity) decreasing further offshore and deeper. This is because *primary productivity* is highest closest to the ocean surface and close to coastlines

**uncertainty** the degree to which a value is unknown, expressed quantitatively (eg a range of temperatures calculated by different models) or qualitatively (eg the judgement by a team of experts on the likelihood of the West Antarctic Ice Sheet collapsing). Uncertainty in climate projections is primarily introduced by the range of projections of human behaviour which determine emissions of greenhouse gases, and the range of results from climate models for any given greenhouse gas

**upwelling** process whereby cold, often nutrient-rich waters from the ocean depths rise to the surface

**vermivorous** to feed on worms, grubs, or insect vermin

**vitellogenic** formation of the yolk of an egg

**viviparous** in animals giving birth to living offspring that develop within the mother's body; in plants producing seeds that germinate before becoming detached from the parent plant, for example some mangroves

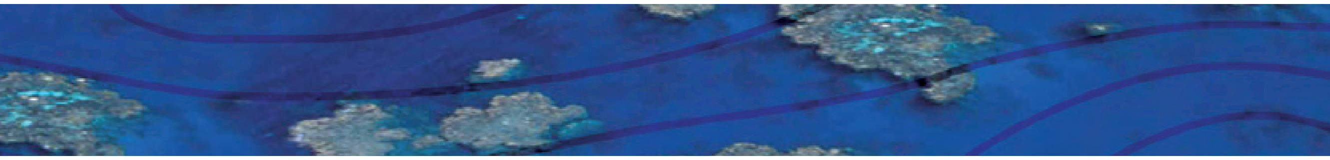
**vulnerability** the degree to which a system or species is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system or species is exposed, its *sensitivity*, and its *adaptive capacity*

**West Pacific Warm Pool (WPWP)** a body of water, which spans the western waters of the equatorial Pacific to the eastern Indian Ocean and holds the warmest seawater in the world

**zoogeographic species concept** closely related species with common ancestry that have developed into true species due to their geographical location

**zooplankton** animal plankton that range in size from a few microns to metres, for example some jellyfish

**zooxanthellae** microscopic single-celled algae (usually dinoflagellates) that form symbiotic relationships with corals, sea anemones, molluscs and several other types of marine invertebrates and provide photosynthetic products (ie energy) to the host animal in return for shelter



# Symbol Glossary

## ANIMALS

- Branching coral
- Plate coral
- Massive coral
- Anenome
- Soft coral
- Gorgonian
- Sponge
- Sponge larvae
- Coral larvae
- Copepods
- Juvenile fish
- Sea birds
- Noddy
- Sooty oystercatcher
- Crested tern
- Pied imperial pigeon
- Bar-tailed godwit
- Capricorn white-eye
- Jellyfish
- Pelagic tunicates
- Butterflyfish
- Rabbitfish
- Coral trout
- Parrotfish
- Damselfishes
- Goby
- Barramundi
- Trevally
- Whiting
- Flyingfish
- Black marlin
- Eel
- Baitfish
- Bull shark
- Mako shark
- Hammerhead shark
- Sawfish
- Blacktip reef shark
- Crown-of-thorns starfish
- Hermit crab
- Brittle star
- Squid
- Nudibranch
- Bivalve/burrowing
- Snail
- Burrowing worms
- Feather duster worm
- Prawn
- Crab
- Polychaete worm
- Christmas tree worm
- Feather star
- Stingray
- Chimaera
- Dolphin
- Turtle
- Koala
- Frog

# Symbol Glossary

## ENVIRONMENT

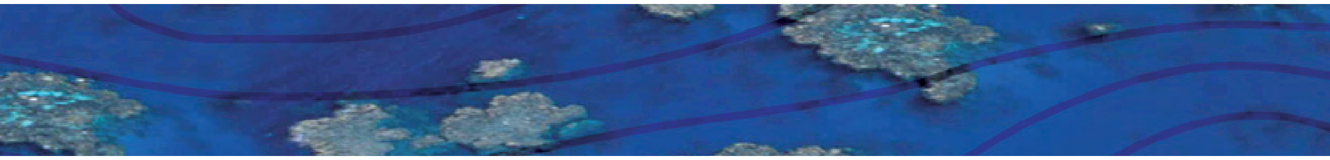
- Sun
- Rain - high/low
- Cyclone/wind
- Calcareous sand
- Silicious sand
- Mud
- Temperature - cool/warm/hot
- pH - alkaline/acidic
- Reef rubble
- Dead coral

## PLANTS

- Mangroves
- Seagrass
- Seagrass seeds
- Fleshy macroalgae
- Turf algae
- Crustose coralline algae
- Wetland vegetation
- Terrestrial vegetation
- Island vegetation
- Casuarina
- Argusia
- Rare terrestrial plant
- Phytoplankton - diatoms
- Phytoplankton - dinoflagellates
- Phytoplankton - mixed
- Trichodesmium
- Heath vegetation
- Grasslands
- Terrestrial weed

## PROCESSES

- Elevated temperature
- Nutrients - pulsed input
- Freshwater - pulsed input
- Sediment - pulsed input
- Sediment scouring
- Sediment - burial
- Sediment resuspension
- Light attenuation/extinction
- Loss
- Flood plume
- Coral recruitment - good/poor
- Upwelling
- Desiccation
- N+P→ Nutrient uptake
- Flux - in/out
- Currents
- Flushing - poor/good
- Mixing
- Wave energy
- Sea level rise
- Flux - low/high
- Limitation - carbon
- $CO_2$ concentration - low/high
- $HCO_3^-$ concentration - low/high
- Salinity - low/high
- Decomposition
- Growth
- Coral growth - slow/rapid
- Timing altered
- Shoreward migration/barrier
- Reef substrate bioerosion



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