Marine Climate Change in Australia
Impacts and Adaptation Responses 2009 REPORT CARD

Coral Reefs and Climate Change

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Anthony K.R.N. and Marshall P. (2009) Coral Reefs and Climate Change. In *A Marine Climate Change Impacts and Adaptation Report Card for Australia 2009* (Eds. E.S. Poloczanska, A.J. Hobday and A.J. Richardson), NCCARF Publication 05/09, ISBN 978-1-921609-03-9.

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Summary: Coral reefs worldwide are sensitive to climate change. There is now overwhelming experimental evidence and strong scientific consensus that climate change will have negative and potentially catastrophic impacts on coral reef structure and ecosystem function. Australia has two of the World's most spectacular coral reef ecosystems: the Great Barrier Reef (GBR) in the east and Ningaloo Reef in the west. Coral reefs also occur south of the GBR (extending to Lord Howe Island) and across northern Australia, including north Western Australia. The threat from climate change to the healthy functioning of these systems represents a significant risk to Australia's natural heritage. Australian coral reefs support billions of dollars of economic activity per year, notably through tourism but also through commercial fishing and recreational activities. Climate change will compromise the ability of coral reefs to sustain the ecosystem goods and services upon which society has come to depend.

The projected increase in the frequency and intensity of warming events (thermal anomalies) will increase the risk of bleaching and mortality of ecologically important coral species. Even under optimistic climate change scenarios (e.g. the B1 scenario of the IPCC), coral reefs are predicted to significantly degrade during this century. For a high carbon-emission path (e.g. the A1FI scenario of the IPCC), there is a high probability that reefs will cease to be dominated by hard corals by the mid to late part of the century. Superimposed on global warming is the growing threat of ocean acidification caused by the accelerated uptake of CO_2 from the atmosphere. Ocean acidification is expected to reduce rates of reef accretion, which is critical for reef maintenance and ecological function. Further, increased fragility of coral skeletons and accelerated rates of reef bio-erosion will increase the susceptibility of reefs to storm damage. Models of reef calcification predict that net rates of reef growth may become negative by the middle of the century.

Sea level rise, increased intensity of storms, reduced water quality, and altered oceanic circulation are important additional impacts of climate change. However, projections of these variables and the functional responses of coral reefs as the century unfolds are less clear. Based on current knowledge about the predicted physical and chemical changes in

the ocean surface during this century, and the biological and ecological processes that drive reef responses, it is timely to now develop appropriate adaptation strategies.

Because there are still significant knowledge gaps in the area of climate change effects and responses by coral reef organisms and ecosystems, the development of adaptation strategies must themselves be adaptive as more knowledge accumulates. Strategies for adaptation are to minimize regional and local-scale impacts of climate change by maximizing reef resilience (i.e. the potential for restoring reef function following disturbances). These include restoring and maintaining high water quality and healthy populations of herbivores to minimize the future risk of community phase shifts from coral to algal dominance.

Introduction

Coral reefs are among the World's most species-rich ecosystems, and are often referred to as the rainforests of the sea (Knowlton 2001). Australia's Great Barrier Reef (GBR) and Ningaloo Reef are among the World's most spectacular and biologically diverse coral reefs. The GBR stretches over 2200 km from the north of Fraser Island to Cape York, covering an area larger than Japan (Fernandes et al. 2005). Australian coral reefs provide critical habitats for a diversity of fauna and flora including around 400 species of corals (Veron 2000), more than 300 species of species of fish (Williams and Hatcher 1983) and more than 5000 species of invertebrates (Hutchings et al. 2007). Preserving Australian coral reefs in an era of climate change is important for societal and conservation reasons: (1) they are unique natural ecosystems, (2) they are national icons, (3) the GBR is a world heritage area (Fernandes et al. 2005), and (4) they contribute significantly to the Australian GDP via tourism and related industries (AccessEconomics 2007).

Coral reefs are highly sensitive to climate change. Two of the principal climate-change factors, global warming and ocean acidification, directly threaten the biological performance and survival of corals and calcareous algae, the main reef-building organisms (Hoegh-Guldberg et al. 2007b). More than 20 years of observational and experimental research indicate that warming and acidification of the ocean surface will affect nearly every aspect of the biology and ecology of key coral reef builders, ranging from organism physiology (Jones *et al.* 1998), bleaching risk (Glynn 1991; Hoegh-Guldberg 1999) rate of calcification (Langdon et al. 2000), survivorship (Harriot 1985; Anthony et al. 2007) and reproduction (Szmant and Gassman 1990; Baird and Marshall 2002a).

Other environmental factors are expected to (and are already observed to) intensify under climate change including tropical storms (Webster et al. 2005), reduced water quality in coastal areas (McCulloch et al. 2003; Fabricius et al. 2005) and sea level rise (Rahmstorf 2007). These factors are likely to interact with ocean warming and acidification in the responses of coral reefs, and may in the long term increase the vulnerability of coral reefs to regional and local scale disturbances (Figure 1).

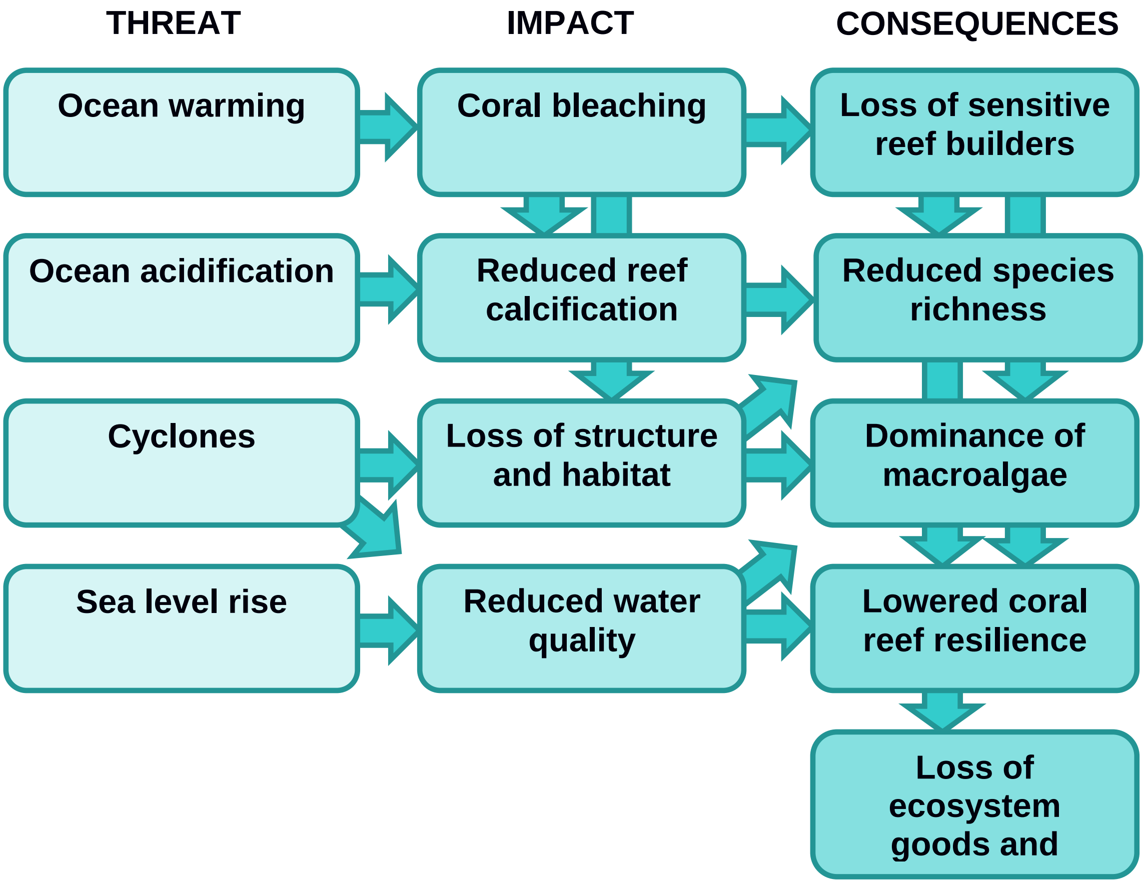

Figure 1. Flow diagram of functional links between climate-change threats, biological and ecological impacts and downstream consequences for ecosystem function. Only a subset of the key links and interactions (arrows) are shown.

The purpose of this review is to summarise observed and predicted impacts of climate change on Australia's coral reefs, and how these impacts will interact with other environmental stressors such as sea level rise, cyclones, water quality and fisheries. The review will also assess the current confidence in predicted impacts on coral reef function for projected climate-change scenarios. Lastly, the review will help identify knowledge gaps and suggest a framework for adaptation strategies in a century of climate change.

Observed Impacts

Global warming and coral bleaching

A prolonged (weeks to months) rise in sea surface temperature above the long-term mean for the season (thermal anomaly) is the primary cause of locally extensive (mass) coral bleaching events (Hoegh-Guldberg 1999; Strong et al. 2004; Eakin et al. 2009; Figure 2). During the past three decades, the world's coral reefs have been impacted by a growing number of thermal bleaching events (Oliver and Berkelmans 2009). The first mass coral bleaching events were reported in the scientific literature in the early 1980s (Yamazato 1981; Glynn and D'Croz 1990). Australia's coral reefs have been impacted by bleaching events in 1980, 1982, 1983, 1987, 1992, 1994, 1998, 2002 and 2006. The 1998 global thermal event devastated a large proportion of the World's coral reefs (Wilkinson 2004), and 1998 and 2002 events were the worst on record for the GBR (Berkelmans et al. 2004).

Figure 2. Periods of warmer than normal summer conditions can lead to extensive bleaching episodes for sensitive species such as branching *Acropora* which are among the most important builders of reef structure and habitat. Photo: Paul Marshall, Great Barrier Reef Marine Park Authority

During the recent history of bleaching events on Australian coral reefs, their occurrence and severity have varied substantially in space and time. Reasons for such variation include (1) regional variation in oceanographic processes (Weeks et al. 2008), (2) reduced light due to cloudiness (Mumby et al. 2001) or water turbidity (Anthony et al. 2004) and a local increase in bleaching resistance due to acclimation, adaptation or selective mortality of susceptible colonies in previous bleaching events (Maynard et al. 2008). Light is an important cofactor in the coral bleaching response (Mumby et al. 2001; Lesser and Farrell 2004) partly because light and temperature impact the same sub-cellular processes in the algal symbionts (Jones et al. 1998). Lastly, bleaching susceptibility also varies between coral species (Marshall and Baird 2000; Loya et al. 2001) and between populations within a species (Glynn et al. 2001; Berkelmans and van Oppen 2006; Ulstrup et al. 2006), further explaining the spatial variation in mass bleaching patterns.

Coral mortality from bleaching

The growth, survival and reproduction of corals rely on their symbiotic relationship with a group of dinoflagellates (*Symbiodinium*) being healthy and functional. The photosynthesis of these endosymbionts supplies the majority of the coral's energy needed for maintenance, growth and reproduction (Muscatine 1990). Coral mortality following bleaching events will occur if warm conditions and high light levels continue, thereby preventing the reestablishment within the coral tissue of productive symbiont densities. Although mass bleaching events on the Great Barrier Reef in 1998 and 2002 were severe, they led to only around 5% mortality overall. However, at some sites in the central GBR populations the mortality of some coral species was 100% (Berkelmans et al. 2004). The recent bleaching event at the inshore Keppel Islands in the southern GBR in 2006 caused around 40% coral mortality, but subsequently showed high recovery (Diaz-Pulido et al. 2009) indicating high local resilience. The link between coral bleaching and mortality is complex and depends on a range of interacting environmental and biological factors (Anthony et al. 2007). One physiological mechanism that provides a functional link is that the coral symbiosis falls into critically low energy status following prolonged bleaching (Anthony et al. 2009). In areas with high availability of plankton as an alternative food source for the corals, however, coral mortality following bleaching events can be reduced in some species (Grottoli et al. 2006).

Ocean acidification

Tropical coral reefs are formed by the accretion of calcium carbonate (limestone) predominantly by scleractinian corals over periods of thousands of years (Veron 1995). The increasing rate of CO_2 uptake by the ocean surface (Sabine et al. 2004) as global atmospheric CO_2 concentrations rise (Raupach et al. 2007) is causing a decline in ocean surface pH (Pelejero et al. 2005) and consequently a shift in the marine carbonate system towards a declining availability of carbonate ions (Feely et al. 2004). Carbonate ions are the chemical building blocks of all marine calcifying organisms (Raven et al. 2005) and the capacity for growth and maintenance of coral reef frameworks are directly related to the availability of carbonate ions in the water (Langdon et al. 2000; Kleypas and Langdon 2006). Ocean acidification is expected to reduce rates of reef accretion (Langdon et al. 2000), which is critical for reef maintenance and ecological function (Kleypas and Langdon 2006), and to increase the susceptibility of reefs to storm damage (Madin et al. 2008).

While corals form most of the aragonitic reef framework and 3-dimensional habitats, groups of calcareous algae also contribute to consolidating the reef matrix (Diaz-Pulido et al. 2007). Crustose coralline algae are particularly sensitive to ocean acidification (Anthony et al. 2008; Kuffner et al. 2008), partly because their skeletons are composed of high-magnesian calcite, which has higher solubility (require a higher carbonate saturation state) than aragonite (Feely et al. 2004). Recent data indicate that ocean acidification during the past two decades have impacted on coral growth rates on the GBR (Cooper et al. 2008; De'ath et al. 2009). Specifically, extension rates for large massive coral colonies (*Porites*) have shown a sudden decline of 13%, which is unprecedented in the past 400 years (De'ath et al. 2009). Impacts of recent ocean acidification on other coral groups or calcareous algae have been less clear as most species do not provide the same opportunity for long-term proxy records.

Cyclones

Damage to coral reefs by severe storms is part of the natural disturbance regime of coral coral reefs (Connell et al. 1997). However, the results of two key studies suggest that the storm regime has already intensified in the past three decades. Firstly, the number of severe cyclones has nearly doubled over the past three decades in all ocean basins

(Webster et al. 2005). Secondly, analyses of power dissipation by individual storms suggest that storm destructiveness has increased dramatically since 1970 (Emanuel 2005). Catastrophic storms are extreme but rare events that are highly unpredictable. However, because the extensive damage they incur to reef ecosystems is likely to last for many years (e.g. Hurricane Katrina in the Caribbean in 2005), they must be incorporated into adaptive management frameworks. Importantly, in addition to their direct damage to reef structure, severe storms also lead to periods of terrestrial run-off and sediment resuspension affecting the turbidity and salinity of coastal reefs in particular (Furnas 2002).

Sea level rise

During the past five decades sea level has risen by 2-3 mm per year worldwide (Bindoff et al. 2007). The impact of sea level rise at this rate will have had an only negligible impact on coral reefs for two reasons. Firstly, large parts of coral reef platforms and barrier reefs are subjected to tidal regimes of several meters (Kleypas 1996) and the vertical growth of reefs in shallow water are periodically constrained by extreme low tide events (Anthony and Kerswell 2007). Secondly, the linear extension rate of the slow-growing coral species *Porites* sp (Barnes and Lough 1999), one of the most important framework builders on Indo-Pacific coral reefs, is an order of magnitude greater than recent rates of sea level rise.

Potential impacts by the 2030s and 2100s

Consequences of warming events and ocean acidification for coral reef builders

Depending on whether an energy conscientious or a fossil-fuel intensive carbon-emission path is used for climate change projections (i.e. IPCC scenarios B1 vs A1FI), the projected increase in the annual frequency and severity of thermal anomalies will lead to a chronically high coral bleaching risk for most coral reefs by the middle to late parts of the century (McWilliams et al. 2005; Donner et al. 2009). Because bleaching involves the partial or total loss of photosynthetic algal symbionts (Hoegh-Guldberg 1999), which supply the majority of the energy for the coral maintenance, growth and reproduction (Muscatine 1990), severe bleaching may result in high rates of coral mortality (McClanahan 2004; Anthony et al. 2009) or reduced levels of growth and reproduction (Baird and Marshall 2002b) . Because the maximum life-span of corals (colonies or clones) ranges from decades to centuries, a significant decline in annual rates of survival`, growth rate and reproduction due to bleaching can have dramatic consequences for coral populations. Although the onset of coral bleaching can be predicted well based on short-term (days to weeks) projections of sea surface temperatures (Eakin et al. 2009), the large amount of stochastic variation associated with longer-term (months to years) SST projections make year-to-year bleaching predictions uncertain. However, the predicted trend in global mean temperatures indicates a gradually increasing bleaching risk, which can be stated with high confidence. The capacity of reef corals to acclimate or adapt to global warming is an area of contention (Buddemeier and Fautin 1993; Baker et al. 2004; Hoegh-Guldberg et al. 2007a; Baird et al. 2009). Experimental and observational studies indicate that thermal adaptation and/or acclimatization is possible. However, given the steepness of the predicted global warming trend and the erratic nature of thermal events, an important yet unanswered question is whether climate change will outpace coral's capacity for adaptation and/or acclimatization.

Ocean acidification

In contrast with the spatially and temporally probabilistic nature of thermal warming driven by a range of short-term climatic variables, ocean acidification is a gradual and steady change in the chemistry of the ocean surface waters (Kleypas et al. 2006). The consistency of results from experimental and modelling studies of reef calcification responses to manipulated CO2 or pH changes (Kleypas and Langdon 2006; Silverman et al. 2009) combined with the lower variability in acidification projection models (Cao and Caldeira 2008), suggest that predictions of reef calcification during the 21st century will have relatively high confidence. Sources of uncertainty are predominantly attributable to regional (Takahashi et al. 2002) and seasonal variation (Feely et al. 2002) in the CO_2 uptake by oceans, and upwelling in coastal or shelf-break areas (Feely et al. 2008). Lastly, because coral reef growth and maintenance is the balance between accretion by calcifying corals and algae and erosional processes (physical and biological), an important consequence of reduced reef calcification and increased coral fragility may be a shift from net reef accretion to net erosion, i.e. reef shrinkage.

Sea level rise

A projected sea level rise of more than a meter during the 21st century may have consequences for reefs only if ocean acidification severely stunts reef growth (Hoegh-Guldberg et al. 2007b) and turbidity levels increase enough to compress the coral's photic zone to very shallow water (Anthony et al. 2004). While reef growth may keep pace with gradual sea level rise, a sudden rise in sea level (e.g. due to ice-sheet collapse,Vaughan and Spouge 2002) may push some coral assemblages outside their viable light niche, particularly if sea level rise is associated with an increase in turbidity due to coastal erosion. Because of the uncertainty in risk estimates for sea level rise, projected impacts on coral can only be assessed with low confidence.

Cyclones

As projections of climate variables driving cyclone formation are complex and associated with uncertainty (Walsh and Ryan 2000), predictions of cyclone activity for Australia during the 21st century can only be done with low confidence at best. However, assuming that the observed trend in storm frequency during the past three decades (Emanuel 2005; Webster et al. 2005) continue, reef assemblages will be facing a future where they will be reset to depauperate and structurally poor assemblages with increasing frequency and intensity. The implications are two-fold. Firstly, a higher cyclone frequency means that reefs on average will be given less time for recovery between cyclones. Secondly, increased cyclone intensity means that reefs will require longer times for recovery to climax assemblages. In addition to the direct physical impacts of storm damage, an intensified cyclone regime is likely to interact with other environmental variables. For example, cyclones lead to flooding events (Furnas 2002) and associated terrestrial run-off of freshwater and dissolved nutrients from coastal catchments (Devlin and Brodie 2005). Further, as coral skeletons are likely to become more susceptible to breakage under ocean acidification the damage from cyclones to reefs structure will be worsened (Madin et al. 2008), even if the cyclone regime remains unchanged.

Multiple Stressors

Climate change threats potentially impact on all organisational levels of the coral reef ecosystem with consequences ranging from lowered physiological performance and survival of individual species to community shifts and lowered reef resilience (Figure 1). In addition to the various direct effects of climate change are their interactions with other stressors. There is now abundant evidence that many non-climate stressors interact to exacerbate the effects of climate stressors (Anthony et al. 2007). For example, corals exposed to pollutants, low salinity, turbidity, sedimentation or pathogens bleach at lower temperatures (Hoegh-Guldberg 1999), and are often less likely to survive a bleaching event. Similarly, coral communities characterised by un-naturally low herbivore biomass or elevated nutrients can be much slower to recover following bleaching-induced mortality, potentially remaining in an algal-dominated state for prolonged periods (decades or more). Conversely, corals that have experienced sub-lethal effects of elevated temperatures can be more susceptible to other pressure such as disease (Bruno et al. 2007). Examples of likely positive interactions include the potentially lowered bleaching risk in cyclonic weather, partly because heavy clouds reduce light stress which add to bleaching risk (Mumby et al. 2001).

Implications for reef resilience

Because climate change is likely to amplify the disturbance regime for coral reefs, the fate of these ecosystems will increasingly be determined by their potential for recovery and long-term maintenance of structure, function and goods and services – i.e. their resilience (Nyström et al. 2000). Resilience-based management requires that management goals for marine ecosystems such as coral reefs be expanded to focus on process (e.g. recruitment success, algal removal rates), as well as state (e.g. coral abundance, density of fish). To preserve Australia’s coral reefs for future generations, it is critical that management efforts are invested into understanding the factors that influence the resilience of ecosystems, and prioritise management efforts toward restoring and maintaining ecosystem resilience. Adaptive resilience-based management is likely to offer the best hope for marine ecosystems in the face of climate change.

Confidence Assessments

Observed Impacts

Warming and coral bleaching

HIGH confidence**.** Numerous experimental and observational studies have established a causative link between thermal anomalies and coral bleaching.

Ocean acidification

MEDIUM-HIGH confidence. Despite this being a young research topic, there is good experimental evidence and consensus that a lowering of aragonite saturation state will lead to reduced reef calcification.

Cyclones

MEDIUM confidence**.** Although studies indicate an increased frequency of severe storms on a global scale during the past three decades, the highly stochastic nature of cyclones prevents drawing an activity trend with high confidence for Australia.

Sea-level rise

HIGH confidence. Because historical coral growth rates and tidal ranges on Australian coral reefs far exceed the observed rise in sea level during the past century, the effect of recent sea level rise on modern coral reef is negligible.

Potential impacts by the 2030s and 2100s

Warming and coral bleaching

HIGH confidence. Global temperature is one of the climate change variables that can be predicted with the highest precision using global carbon circulation models (Meehl et al. 2007). In view of this and the large body of experimental and observational studies that have established a strong causative link between temperature and coral bleaching, it can be stated with high confidence that coral bleaching risk during this century will increase. Although studies have demonstrated that acclimation or adaptation to increased temperatures do occur in natural coral populations, the unprecedented rate of ocean warming is likely to outpace capacity of corals to acclimate or acclimatize.

Ocean acidification

HIGH confidence. The projection of ocean chemistry changes under climate change is strongly related to projected atmospheric CO_2 concentrations, ocean temperatures and oceanography (Cao et al. 2007). Models combining CO_2 and temperature projections for IPPC scenarios and reef calcification responses produce consistent predictions of declining reef growth for the century (Kleypas et al. 2006; Silverman et al. 2009).

Cyclones

MODERATE confidence**.** The stochastic nature of cyclones and the complexity of meteorological forecasting place severe cyclones in the category of rare but extreme events. Although individual storms are difficult to predict, the growing trend in storm intensity during the past three decade (e.g. Emanuel 2005) suggests that the physical disturbance regime once a natural part of coral reef dynamics, will be raised substantially.

Sea-level rise

LOW confidence. While it is certain that sea level will increase over this century, the risks from sea level rise are uncertain as they depend on whether the rise is gradual or sudden, whether substantial ice-sheet collapse will occur, and on the side-effects of other processes such as land erosion and increased turbidity which may impact reefs in coastal waters.

Adaptation Responses

Many coral reef species, habitats and processes are highly vulnerable to the effects of climate change, putting at risk globally-significant biodiversity and heritage values (Australian National University 2009). Additionally, and consequently, climate change threatens to undermine the ability of Australian coral reefs to deliver the ecosystems goods and services that support many billions of dollars in economic activity in regional Australia. Taking measures to facilitate adaptation of coral reef ecosystems, and building the adaptive capacity of reef-dependent industries and communities, is of great national interest.

Mitigating the rate and extent of climate change remains an essential national and global priority if coral reefs are to retain a semblance of their current beauty and utility through this century. However, even if the most optimistic climate scenarios are achieved, substantial changes will occur to coral reef ecosystems. Australia’s coral reefs may fare better than most around the world, but impacts are inevitable.

Improved governance arrangements and adaptation of management approaches are required if reef ecosystems are to have the best chance of coping with climate change. Many local activities and stresses exacerbate the impacts of climate change, and effective management of these can have a large bearing on the ability of systems to resist or recover from climate change impacts. Poorly managed systems are less likely to recover and more likely to collapse as a result of external stresses from climate change. Therefore, the effectiveness of efforts to reduce local stresses, such as water pollution, fishing and habitat damage, is even more critical in the face of climate change (Marshall and Schuttenberg 2006).

Climate change is certain to cause further degradation to marine ecosystems in the course of this century. However, not all sites or habitats are equally affected by climate-related stresses, and sites that are naturally resistant to these stresses will become increasingly valuable to ecosystem resilience. Sites that might serve as climate change refugia will warrant especially effective management to protect them from other threats. Adapting management of coral reefs to accommodate these new approaches and priorities is crucial to their future (Marshall and Johnson 2007).

Changes to coral reef ecosystems will inevitably affect the communities and industries that depend on them (Fenton et al. 2008). Coastal communities throughout tropical and sub-tropical Australia are dependent on coral reefs as a 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 coral reefs for recreational opportunities, and for less quantifiable 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, and especially on their capacity to adapt to the effects of climate change.

Adaptive capacity is one of the most critical aspects of resilience in social systems (Folke et al. 2002). Resilient social systems have the ability to learn and adapt, and resilient people and communities recognise, learn and even benefit from the new possibilities that change brings. Reef-dependent 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 coral reefs, 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 the effects of climate change. This understanding will provide the foundation for strategic initiatives that can build the resilience of communities and industries that depend on Australia’s coral reefs, and thus reduce the social and economic impacts from climate change (Marshall and Marshall 2007).

Formal adaptation plans are being implemented to help the social-ecological systems based on Australia's coral reefs deal with climate change. The Great Barrier Reef Climate Change Action Plan, supported through the COAG National Climate Change Adaptation Framework, outlines a 5-year program to develop and test strategies to build ecosystem resilience and the adaptive capacity of communities and industries that depend on the Great Barrier Reef. Under this Plan, key stakeholder groups are initiating sector-specific adaptation plans, including for tourism and fisheries on the Great Barrier Reef.

Knowledge Gaps

The following is a list of research and management needs that identify specific knowledge gaps:

- Multidisciplinary research is needed to unravel how global climate change interacts with local and regional environmental factors.
- Integrated approaches to better understanding the links between organism, population, community and ecosystem levels.
- Experimental resilience studies to strengthen predictions of thresholds for phase shifts under climate change
- Sensitivities of ecosystem function and goods and services to climate change and local disturbance regimes
- Acclimatization and/or adaptation potentials of reef building organisms to ocean acidification
- Viable management options for ocean acidification
- Development of decision-support systems to enable managers and policy-makers to manage in the face of uncertainty
- Improved systems and approaches for integrated assessments of climate vulnerability
- Improved systems and approaches for integrated adaptation planning

Further Information

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