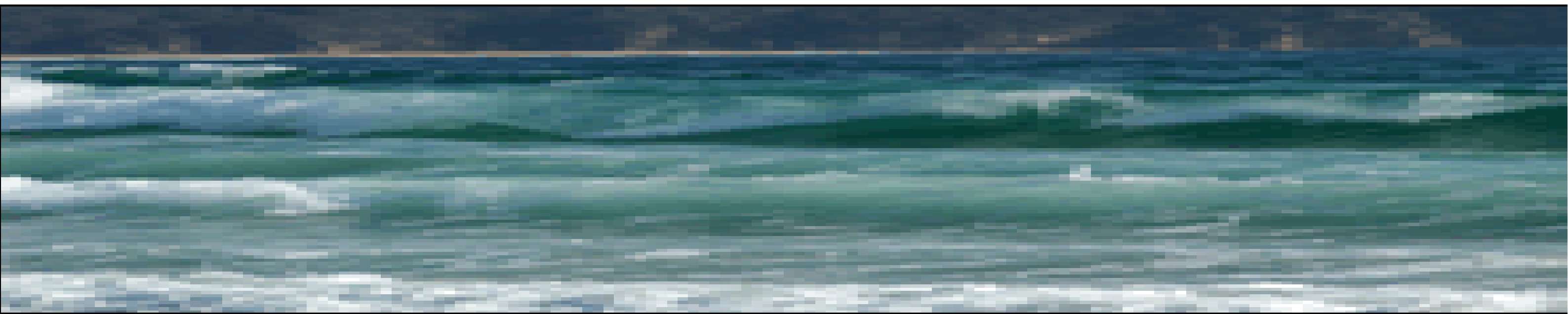
Australian Government

Department of the Environment and Heritage
Australian Greenhouse Office

Impacts of Climate Change on Australian Marine Life

Part A: Executive Summary



Editors:
Alistair J. Hobday, Thomas A. Okey, Elvira S. Poloczanska,
Thomas J. Kunz, Anthony J. Richardson

CSIRO Marine and Atmospheric Research
report to the
Australian Greenhouse Office , Department of the Environment and Heritage

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This report is in 3 parts:
Part A. Executive Summary
Part B. Technical Report
Part C. Literature Review

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GLOSSARY OF TERMS USED IN THIS REVIEW

Benthic	Referring to the sea floor; usually fauna that lives on the seafloor, e.g. sponges, crabs and flatfish.
Demersal	Oriented to the sea floor, not necessarily living on or in it, e.g., some fishes.
Elasmobranch	Subclass of fishes, comprising sharks, rays and the Chimaera. The skeleton is mainly cartilaginous. Also known as chonricthyians.
Endemic	Species occurring only in a particular region, but nowhere else in the world.
Epibiont	An organism living on another organism.
Eutrophic	Environment or region where productivity is fast due to high nutrients.
Foundation species:	Species that form a habitat structure for other species. Examples include kelp, mangroves and coral reefs.
Mixed layer	Upper portion of the ocean (typically 20-200 m thick) where wind and convection mix the water and its constituents (e.g. nutrients, salts, microplankton). As a result, temperature and salinity are relatively constant within this layer.
Oligotrophic	Poor nutrient environment or region where a lack of nutrients such as nitrate restricts biological productivity.
Ontogenetic	Occurring during successive stages of an animal's life.
Pelagic	The open sea beyond the continental shelf and comprising the water column (all of the sea except that near the coast or the sea floor). Pelagic fish species include tuna and sardines.
Pg, petagram	Equal to 10^{15} grams or 1 gigatonne – 1 billion tonnes.
Phenology	The timing of events in an animal's life, such as when it lays eggs, migrates, or shows peaks in abundance. As these events may be sensitive to climate, phenology studies provide evidence of climate impacts on biology.
Piscivorous	Fish eating.
Resilience	Refers to the amount of disturbance or stress that an ecosystem or species can absorb and still remain capable of returning to its pre-disturbance state.
Scenario	Scenarios outline different possible futures for the planet. Scenarios can be very simple (e.g. CO_2 increasing at 1 % per year) or more realistic (e.g. the Intergovernmental Panel on Climate Change (IPCC) SRES scenarios). Which scenarios should be considered most realistic is currently uncertain, as projections of future CO_2 and sulphate emissions are uncertain. Scenarios are used in coupled ocean-atmosphere models to project future climate changes.
SOI	Southern Oscillation Index. An indicator based on the atmospheric pressure gradient between Darwin and Tahiti. A positive index corresponds to an anomalously high pressure difference between the two locations. Used as an indicator of El Niño activity.
Stratification	The upper water column typically comprises several layers differing in temperature and/or salinity. Density differences between the layers restrict exchange of water, including nutrients and microplankton, among those layers. Increasing density differences enhance stratification, whereas increasing wind reduces stratification.
Teleost fish	Bony fishes with rayed fins; most fishes that are not sharks or rays.
Thermocline	Depth at which the water temperature changes most rapidly, typically at the base of the mixed layer.
Upwelling	Movement of water from depth to the surface, usually enriching upper waters with nutrients from deeper waters.
Zonal	Along lines of latitude (east-west direction); the opposite is meridional (north-south direction).

KEY FINDINGS

Climate change is expected to have considerable impacts on marine life and marine ecosystems. There will inevitably be flow-on implications for human societies and economies, particularly those in regional Australia highly dependent on the marine environment and its resources.

Notable impacts of climate change on marine biodiversity have been observed throughout the world – principally due to the existence of long-term data series. Evidence from Australian waters is sparse, mainly due to a lack of historical long-term data collection. Importantly, little modelling has been conducted to predict future changes in Australian marine ecosystems and this remains a critical gap. This report identified six key questions that need to be addressed by future modelling and monitoring programmes:

1. How will the distribution and abundance of marine species and communities alter with climate change?
    - Changes have already been observed in some regions, for example in the south-east.
2. Which species are candidate indicators for climate change impacts?
    - Species that provide structural integrity of habitat, such as corals and kelp, or species that have key ecological roles, such as phytoplankton that drive food chains, would be effective sentinals of climate change impacts.
3. Within large marine domains, where are sensitive areas or hotspots of change?
    - Preliminary analysis from this report suggests that there is regional variability in sensitivity or vulnerability to climate change impacts, with the Tasman Sea in the south-east and the east coast identified as examples of hot-spots of change.
4. How will ocean productivity alter with climate change?
    - International studies indicate that productivity of marine systems will be affected by climate change, and this report provides evidence that Australia's already low productivity is likely to decrease further.
5. How would reduction in non-climate related stressors increase ecosystem resilience to climate change?
    - This report recommends that a reduction in non-climate stressors such as extractive or polluting activities is likely to build ecosystem and species resilience to the impacts of climate change.
6. To what extent will marine climate change impacts affect socially and economically important uses of Australian marine ecosystems?
    - The report provides support that climate change effects are likely to affect social and economic uses of the marine environment, with Australia's fisheries and tourism industries likely to be most affected.

1. INTRODUCTION

Australia is truly a maritime nation; over 90% of the population of 20 million live within 120 km of the coast and Australia has sovereign rights over approximately 8.1 million km^2 of ocean. Australia's oceans generate significant economic wealth; about $52 billion per year or 8% of gross domestic product through activities such as fisheries (Figure 1–1), tourism and recreation, shipping and offshore gas and petroleum extraction. Fisheries and aquaculture are important industries in Australia, both economically (gross value over $2.5 billon, Figure 1-2) and socially. Marine life and ecosystems also provide invaluable services including coastal defence, nutrient recycling and greenhouse gas regulation valued globally at $27 trillion per annum (Constanza et al. 1997). Similarly, the annual economic values of Australian biomes have been estimated as: open ocean $464.7 billion, seagrass/algal beds $175.1 billion, coral reefs $53.5 billion, shelf system $597.9 billion and tidal marsh/mangroves $39.1 billion (Blackwell 2005). Climate change is a threat to the economic and ecological sustainability of fisheries, aquaculture and tourism, as well as to the critical ecosystem services such as coastal defence and greenhouse gas regulation. Unfortunately, there is little consolidated knowledge of the potential impacts in Australia.

Figure 1-1: Map of the Australian Fishing Zone, © Commonwealth of Australia 2005. The Heard Island and McDonald Islands fishery area is off the map and not shown here.

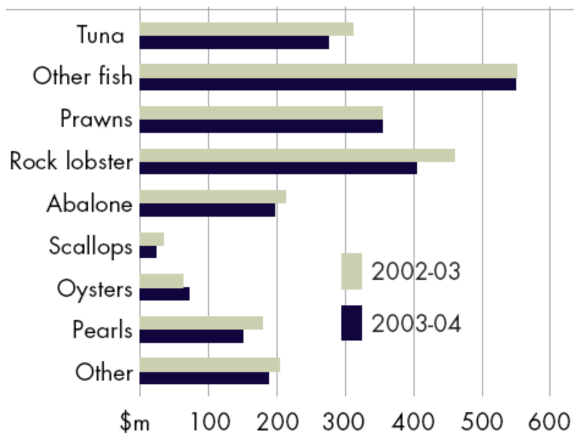


Figure 1-2: Value of Australian fisheries products (from ABARE 2005).

This report provides the first broad synthesis of current knowledge of climate change impacts on Australian marine life. We assessed climate impacts by (1) reviewing the scientific literature on climate change impacts on Australian marine life in the context of known impacts elsewhere in the world, and (2) developing an indicator-based ranking of the vulnerability of marine life to projected climate changes in the seven Large Marine Domains adjacent to continental Australia. The area covered by this report is effectively from the intertidal zone to the deep sea within Australia's 200-nautical-mile Exclusive Economic Zone. This report is comprises three separate parts:

Part A. Executive Summary
Part B. Technical Report
Part C. Literature Review

2. FEATURES OF THE AUSTRALIAN MARINE ENVIRONMENT

The Southern Hemisphere differs greatly from the Northern Hemisphere in its characteristics. In the Northern Hemisphere the ratio of land to water is about 1 to 1.5, while in the Southern Hemisphere the ratio is about 1 to 4, which greatly impacts the interaction between the marine and terrestrial environment. Further, much of Australia is sparsely populated and the interior is predominantly desert compared to the vast, heavily vegetated or populated expanses of land in the Northern Hemisphere. Because of the unique geological, oceanographic and biological characteristics of Australia, conclusions from climate impact studies in the Northern Hemisphere may not be directly transferable to Australian marine systems.

2.1 Influences on the physical marine environment

Australia is unique among maritime countries in that both the west and east coasts are bounded by major poleward-flowing warm currents (Figure 2-1), which have considerable influence on marine flora and fauna. The East Australian Current (EAC) originates in the Coral Sea and flows southwards before separating from the continental margin to flow northeast and eastwards into the Tasman Sea (Ridgway & Godfrey 1997, Ridgway & Dunn 2003). Eddies spawned by the EAC continue southwards into the Tasman Sea bringing episodic incursions of warm water to temperate eastern Australia and Tasmanian waters (Ridgway & Godfrey 1997). The Leeuwin Current flows southwards along the Western Australia coast and continues eastwards into and across the Great Australian Bight reaching the west of Tasmania in the austral winter (Ridgway & Condie 2004). The influence of these currents is evident from the occurrence of tropical fauna and flora in southern Australian waters at normally temperate latitudes (Maxwell & Cresswell 1981, Wells 1985, Walker & Prince 1987, Dunlop & Wooller 1990, O'Hara 2000, Griffiths 2003). The importance of these major currents in structuring marine communities can be seen in the present biogeographic distributions of many species, functional groups and communities.

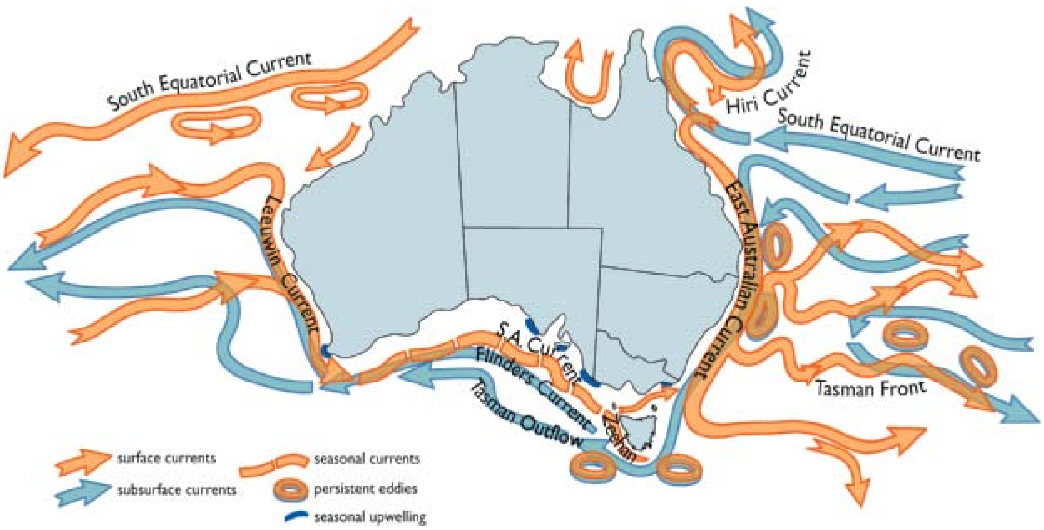


Figure 2-1: Major currents and circulation patterns around Australia. The continent is bounded by the Pacific Ocean to the east, the Indian Ocean to the west and the Southern Ocean to the south. Figure courtesy of CSIRO.

Because of these currents, waters surrounding Australia are largely of tropical and subtropical origin and are mostly nutrient poor (oligotrophic), particularly with respect to nitrate and phosphate. Australian soil is generally low in nutrients and this, together with the high variability in rainfall, results in little nutrient input into the surrounding sea from terrestrial sources. The generally oligotrophic status of Australian marine waters contrasts with many mid-latitude productive coastal areas around the world. This contrast is particularly strong on the western coast of Australia where the oligotrophic Leeuwin Current flows southward (poleward) suppressing upwelling. Highly productive equatorward flowing eastern boundary currents associated with upwelling systems are characteristic of all other major ocean basins. The impact of changing productivity on marine oligotrophic systems is largely unknown; they may not be as resilient to stress and disturbance, including climate change, as more productive systems that commonly experience considerable interannual variability.

Large-scale oceanographic and atmospheric drivers play a key role in regulating Australian marine ecosystems. Such drivers include the El Niño Southern Oscillation (ENSO), circulation patterns, rainfall and the coupled runoff of sediment and nutrients, frequency and intensity of shelfbreak and topographic upwelling, frequency and intensity of cyclonic disturbance, and wind stress and its effects on sediment resuspension, vertical mixing, and coastal current dynamics. These atmospheric and hydrodynamics processes interact in complex ways, influencing the physical and chemical attributes of the water column that regulates plankton productivity and community structure and thus the food available to higher trophic levels both in the water column and on the sea floor, as well as the larval dispersal of almost all marine invertebrates (Figure 2-2). For example, aeolian dust input may be an important regulator of coastal primary production. In nutrient limited regions typical of Australian waters, the atmospheric supply of iron may influence phytoplankton biomass and composition (Jickells et al. 2005). Climate-induced changes in wind or rainfall may thus have disproportionately large consequences for the Australian coastal ocean, making it difficult to easily generalise from knowledge elsewhere.

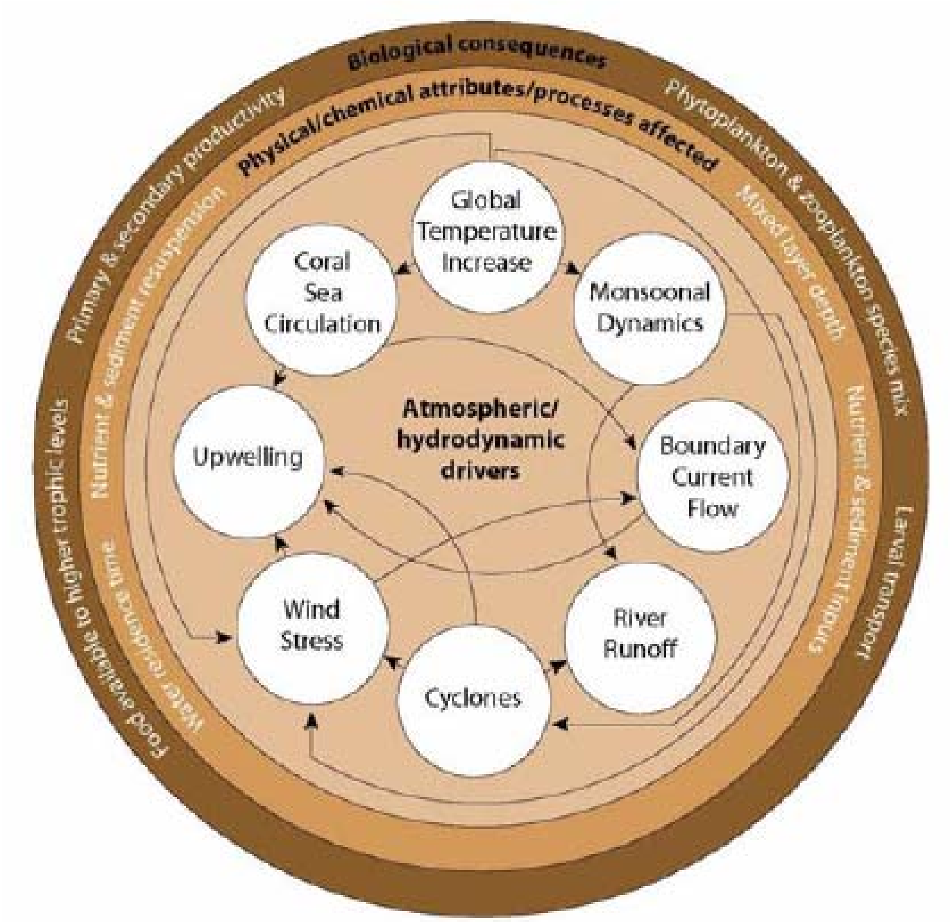


Figure 2-2. Example of complex inter-relationships between atmospheric/hydrodynamic drivers and physical/chemical processes, together with their biological consequences (from McKinnon et al. in press).

2.2 Australian marine biomes

Including fringing islands, Australia has a coastline of almost 60,000 km that spans from southern temperate waters of Tasmania (~ 45°S) to northern tropical waters of Cape York, Queensland (~ 10°S). The marine life inhabiting Australia's ocean realm can be classified into *bioregions* or *Large Marine Domains* based on the composition of the various biological assemblages. This biological composition and the resulting delineation indicate particular coastal conditions and oceanographic characteristics. Australia's Large Marine Domains can thus be thought of as *biomes*, which are areas defined by biological assemblages and the prevailing climate.

A marine bioregionalisation for Australia has been developed during the last decade (CSIRO 1996, Lyne et al. 1998, Lyne and Hayes 2005) to provide a framework for implementation of management and policy on a national and regional basis and to provide an enhanced scientific understanding of Australia's marine life. Accordingly, this bioregionalisation is a useful framework for this report, especially for our ranking of the vulnerability of marine life to climate change (Figure 2-3).

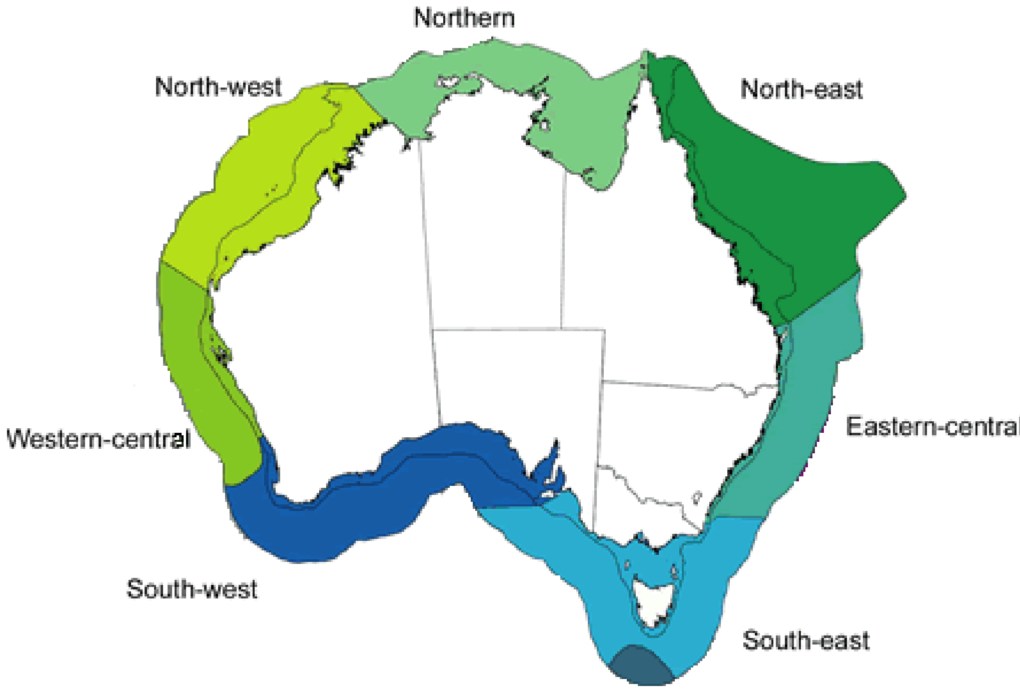


Figure 2-3: The seven Large Marine Domains adjacent to continental Australia (modified from CSIRO 1996). This figure excludes Australia's five other Large Marine Domains surrounding Lord Howe, Norfolk, Macquarie, and the Sunda Islands, and waters adjacent to the claimed portions of continental Antarctica.

2.3 Climate influences on species and communities

Anthropogenic global climate change has profound implications for the survival and productivity of marine populations, communities and ecosystems. An idea of the relative importance of major climate stressors to marine populations can be garnered from the review by Harley et al. (2006). They surveyed the marine ecological literature that addressed climate-related issues and found that studies on temperature change far outnumber those for all other climate stressors (Figure 2-4). Although differences in ease of measurement might partially bias these results, we suggest that they reflect a real relative importance of stressors. Much climate-related research has focused on potential shifts in abundance, distribution and timing driven directly by temperature. The situation is more complex, however, with a suite of other variables that are also important. For example, changes in ocean chemistry may be more important than changes in temperature for the performance and survival of many organisms with calcium carbonate structures. Ocean circulation, which drives larval transport and influences productivity, will also change in the future, with important consequences for population dynamics. Further, climatic impacts on a few leverage species, such as foundation species like corals or kelp, may result in sweeping community-level changes. In general, climate model simulations of climate change predict oceanic warming; an increase in oceanic stratification; changes in circulation and convective overturning; and changes in cloud cover and sea ice and thus light supply to the surface ocean. All these will cause significant and sometimes dramatic alterations in marine ecosystems (Bopp et al. 2001, Boyd & Doney 2002, Sarmiento et al. 2004).

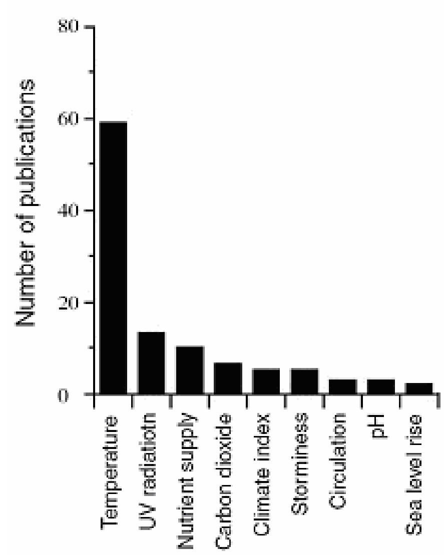


Figure 2-4: Publication trends of climate-related research in the marine ecological literature from 1991-2004 (from Harley et al. 2006).

2.4 Key non-climate change stessors

Australia's marine life is affected by a number of non-climate related human activities, and in some cases these stressors strongly influence species and biological communities. These activities and impacts can be classified into broad categories of fisheries, pollution and habitat degradation.

Australian fisheries include various commercial (Caton and McLaughlin 2004; see also Figure 1-2), recreational and indigenous fisheries (Henry and Lyle 2003). Each of these uses a spectrum of gears and differs in their magnitudes of catches. Fisheries impact marine ecosystems in two major ways: they kill and remove marine organisms directly and they modify habitats. Some gears impact habitat considerably, as in the case of bottom trawling on deep-sea coral or sponge gardens. Vulnerable habitat can consist of both living and non-living structures.

Pollution, here defined broadly to include all types of runoff and the associated sedimentation, affects Australia's marine ecosystems both locally and regionally depending on the type of pollution. Point-source pollution is associated with industries and municipal outfalls such as those for sewage. Non-point source pollution is usually freshwater runoff from urban and agricultural areas. The latter type of pollution is strongly associated with habitat disruption and degradation. For example, the structure and function of coastal watersheds can be modified considerably by agriculture, urban development, and deforestation leading to dramatically increased erosion and nutrient runoff in addition to the non-point source pollutants from other human activities. Virtually all of Australia's population and industries are situated along the coastal fringe or rivers that drain into the sea, and so the effects of pollution on marine ecosystems can be severe and can combine with the effects of other stressors (discussed later). Shipping and oil development are other sources of pollution. Sound pollution is also an impact receiving greater attention. Zann and Sutton (1995) have reviewed the effects of different types of pollution on Australia's marine environment.

The other broad class of non-climate change stressors is habitat modification and destruction including intertidal, shallow sub-tidal, and estuarine modifications as well as seafloor trawling and other disturbances. Estuaries, mangroves, seagrass beds, and kelp forests, for example, are integral features of marine ecosystems that provide a variety of critical ecosystem services such as nursery grounds, primary production, and adult habitats for whole suites of marine organisms, as discussed in Part C (Literature Review). These and other biotic features and habitats are increasingly threatened by the burgeoning coastal development around Australia's shores, and this habitat destruction can considerably decrease the resilience of Australia's marine ecosystems to climate change impacts.

3. AUSTRALIAN MARINE CLIMATE CHANGE PROJECTIONS

Global climate models developed in Australia and internationally all project more than a doubling of global atmospheric CO_2 by the end of this century compared with pre-industrial levels (280 ppm). Current atmospheric levels have already risen to 380 ppm. Further rises will have dramatic consequences for physical and chemical stressors of Australian marine systems; climate change projections are summarised in Table 3-1. Increases in atmospheric CO_2 levels will make the ocean more acidic, adversely affecting many organisms that use calcium carbonate for their skeletons and shells, including corals, molluscs and some phytoplankton species.

Global climate models predict that the greatest warming in the Southern Hemisphere oceans will be in the Tasman Sea associated with a strengthening of the EAC. This feature is present in all IPCC climate model simulations and is driven by a southward migration of the high westerly wind belt south of Australia. This robust prediction has already resulted in serious consequences for marine life in the Tasman Sea and other southern Australian waters. Warming will not only affect surface waters, but will also penetrate deep into the ocean, warming waters down to 500 m and beyond (Table 3-1). This will have major consequences for bottom-dwelling fish and invertebrate communities. Climate change will also substantially modify other physical variables important for regulating marine ecosystems including incident solar radiation (through cloud formation), winds and mixed layer depth.

Table 3-1: Projected changes in physical and chemical characteristics of Australia's marine realm by 2070 from the CSIRO Mk 3.5 model (see Part B of this report for more detail)

Physical climate change indicators	**Projected climate change impacts by 2070**
Sea Surface Temperature	Waters around Australia warm by 1-2°C, with greatest warming in SE Australia/Tasman Sea due to strengthening of EAC
Temperature at 500 m depth	Warming of 0.5-1°C
Incident solar radiation	There will generally be more incident solar radiation on the sea surface in Australian waters. The increase will be between 2 and 7 units W m^{-2}
Mixed layer depth	Almost all areas of Australia will have greater stratification and a shallowing of the mixed layer by about 1 m, reducing nutrient inputs from deep waters
Surface winds	An increase of 0-1 ms^{-1} in surface winds.
Surface currents	A general decline in the strength of surface currents of between 0-1.2 ms^{-1}
pH	A decline in pH by 0.2 units

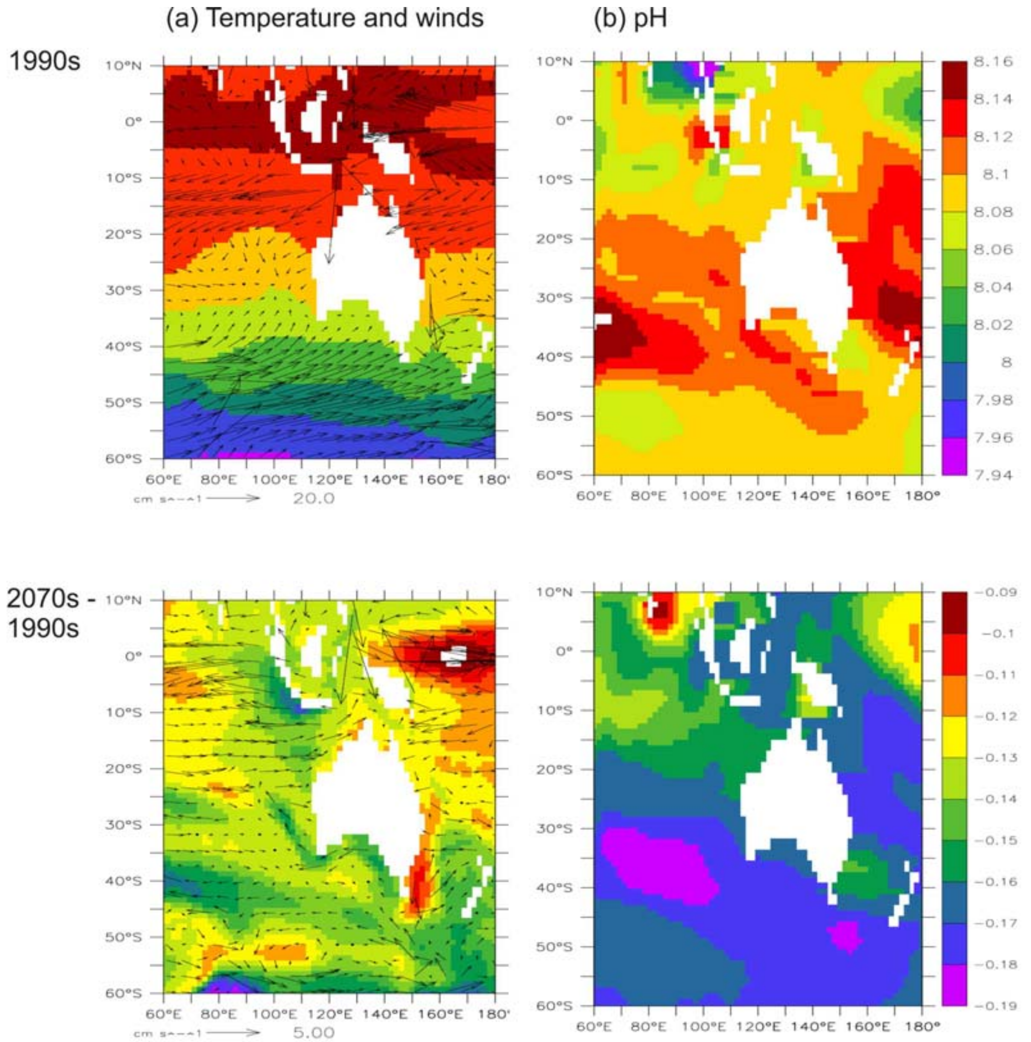


Figure 3-1: (a) Average Sea Surface Temperature and winds (°C) for the 1990s and the change in SST and winds between the 2070s and 1990s, and (b) Average pH for the 1990s and the change in pH between the 2070s and 1990s.

4. VULNERABILITY OF MARINE LIFE TO CLIMATE CHANGE

We provide two separate approaches for assessing vulnerability of marine life. The first method described here is a bioregional approach, whereby we score the vulnerability for each Large Marine Domain based on 29 quantitative indicators categorised into five dimensions of vulnerability. Indicators represented different aspects of projected climate change, species endemism, and anthropogenic stressors such as pollution and fisheries (see Box 1 and described more fully in Part B). The second method comprises a literature review of the major groups of marine life found in Australian waters (Part C of this report). These two distinct approaches focus on different aspects of vulnerability – one emphasises geographic areas that may be most at risk and the other focuses on the most vulnerable marine groups.

Box 1: Method for Rating Vulnerability of Marine Life

Five dimensions of vulnerability were selected to represent the different aspects of stress that impact marine life and the different characteristics that mediate stressors. These were:

- biological
- regional characteristics
- climate change
- fishing stress
- other anthropogenic stressors.

Each dimension of vulnerability comprises four to eight indicators that were scored from 1-5 for each of the seven domains. Climate change indicators (1990s to 2070s), namely temperature, salinity, pH, mixed layer depth, currents, solar radiation, winds and freshwater flux, were obtained from the CSIRO Mk 3.5 model (see this report, Part B). Other indicators were derived from additional datasets around Australia. These indicators were combined to give an overall vulnerability for each marine domain (see Figure 4-1).

Climate impacts on particular species or groups do not occur in isolation and can result in extensive cascading effects and complex interations. Some types of marine life, such as corals, are foundation species that support a diverse range of fauna and flora by providing a living habitat architecture. Others such as phytoplankton and zooplankton function as primary producers at the energetic 'base' of marine foodwebs. Still others, such as mangroves, seagrasses and kelps, serve both functions. Most of these groups support higher trophic levels such as pelagic and demersal fishes, seabirds, turtles, and marine mammals, in addition to invertebrate organisms that inhabit the soft or hard sea floor. The vulnerability of marine life to climate change will vary by species, biological community and location. We are not able to capture all these complexities in our vulnerability rating system of the seven large marine domains surrounding continental Australia, although we have tried to include the importance of foundation species.

This rating system indicated that the Eastern-central and South-east domains were the most vulnerable to both climate impacts and overall exposure, although all seven domains tested were rated as moderately vulnerable to climate change (Figure 4-1, Table 4-1). Our approach allowed identification of the principal stressors for each domain. In each region, policies can be targeted toward major non-climate stressors that would mitigate future impacts of climate change, and will help focus future research effort.

There are some caveats with interpreting this analysis. For example, we could not include some of the critical stressors we identified as particularly important in our review (such as pH) in the bioregional analysis because robust projections were difficult to obtain. Further, one can not combine directly the ratings for our vulnerability analysis here and the literature review of the major groups of marine life. For example, some groups that were identified as most vulnerable from the literature review (e.g. corals) are rare or absent from bioregions that were shown to be most vulnerable (e.g. Eastern-central and South-east domains). However, we believe that these analyses show complementary aspects of vulnerability and both types should be considered when making decisions about where and on what to concentrate future effort.

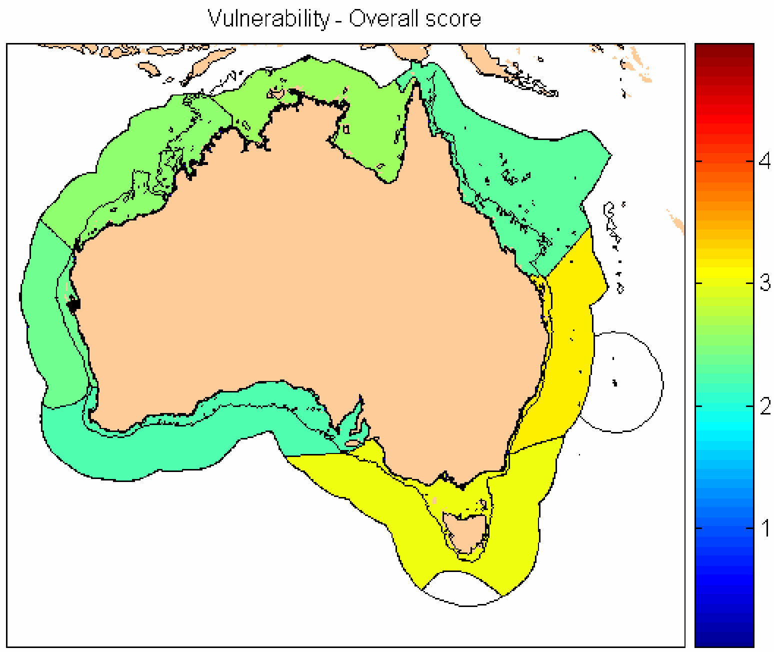


Figure 4-1: Overall vulnerability of marine life to climate change and other stressors in each of Australia's seven large marine domains. See Box 1 and Part B of this report for more details.

Table 4-1: Final scores for particular dimensions of vulnerability of marine life in each of Australia's seven large marine domains (on a scale from 1-low to 5-high) together with overall and ranked vulnerability (ranking 1-most vulnerable to 7-least vulnerable).

Vulnerability Dimension	Northern	North-east	North-west	Western-central	Eastern-central	South-west	South-east
Biological	1.25	2.75	2.75	3.25	3.75	2.00	2.00
Regional	3.00	1.00	2.00	2.00	1.67	2.67	2.33
Climate Change	3.45	3.89	3.48	2.76	4.35	1.65	3.31
Fishing	3.39	1.57	1.01	1.32	3.17	2.04	3.84
Other Anthropogenic	2.38	2.50	3.75	2.63	3.13	2.75	3.88
Overall Vulnerability	2.68	2.33	2.60	2.43	3.21	2.28	3.07
Ranked Vulnerability	**3**	**6**	**4**	**5**	**1**	**7**	**2**

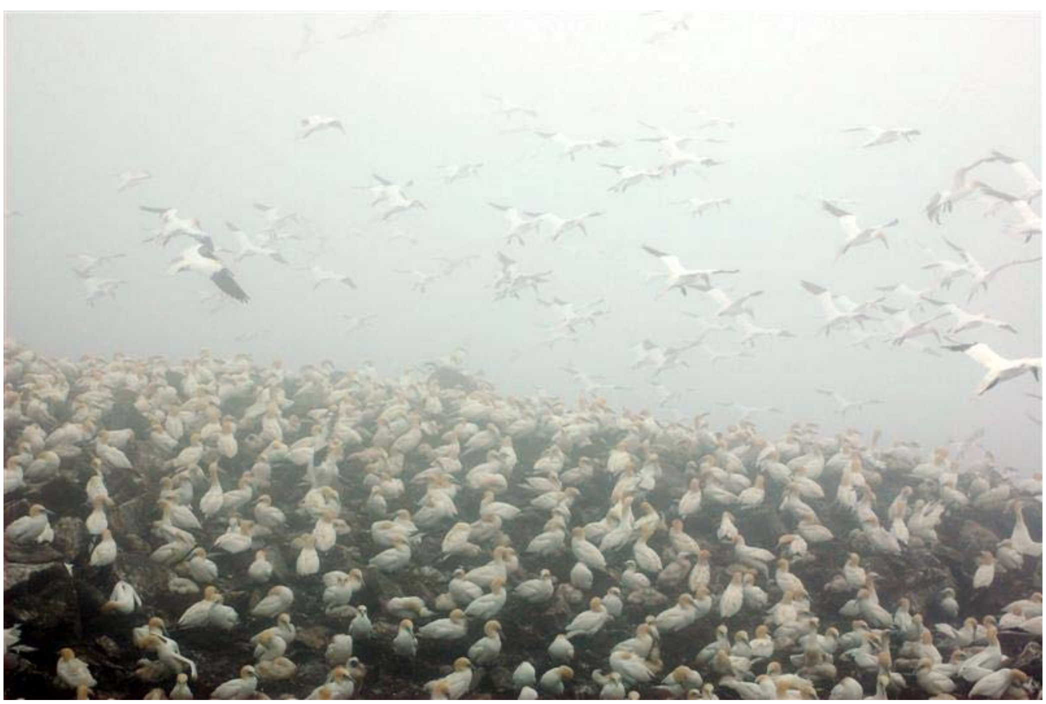
5. EXPECTED IMPACTS ON MARINE LIFE

A global literature review revealed substantial impacts on marine life are already apparent (Part C). For example, distributions of fish, plankton, and rocky shore intertidal species are all shifting polewards in the North Atlantic (Beaugrand et al. 2002, Bonnet et al. 2005, Mieszkowska et al. 2005, Perry et al 2005), while the timing of Antarctic seabird breeding and peak migration dates are also shifting (Barbraud & Weimerskirch 2006). However, there are relatively few observations of climate change impacts on Australian marine life. We do know that climate change is already moving tropical and temperate phytoplankton southwards off eastern Australia (Blackburn & Cresswell 1993, Blackburn 2005). Recent warming of tropical waters has led to repeated mass coral bleaching events on the Great Barrier Reef and elsewhere, a phenomenon not observed globally before 1979 (Hoegh-Guldberg 1999, Knowlton 2001). Declines of giant kelp forest communities in coastal waters of eastern Tasmania have been associated with changing oceanographic conditions including warming temperatures (Edyvane 2003, Edgar et al. 2005), and range expansions have been observed in seabird species along the west coast of Australia (Dunlop & Wooller 1986, Dunlop 2001).

Climate change may strongly modify biogenic habitats such as those formed by foundation species and assemblages including mangroves, tropical corals, kelps, and cold water corals. Further, climate change impacts on dominant producer groups that are sensitive to climate change such as phyto- and zooplankton will have repercussions throughout the marine foodweb. The relatively productive southeastern temperate phytoplankton province is likely to retreat west of Tasmania by the 2070s, with concomitant reductions in foodweb productivity including fisheries yeild. Given the projected warming of Tasman Sea waters and deep waters further south, this area may be particularly sensitive to climate change. Among species most at risk are the coastal species endemic to south-east Tasmania; this area has the highest localised level of endemism in Tasmania and probably in Australia (Edgar et al. 1997).

6. SYNTHESIS OF MAIN IMPACTS AND RECOMMENDATIONS

In this section we provide summary findings from the review of climate impacts on thirteen groups of marine life and habitats around Australia in Part C. The present section includes one-page synopses of these literature reviews including the ecology, projected climate change impacts based on laboratory, modelling and field work (often largely from overseas studies), conspicuous information gaps, and research and management recommendations.



6.1 Phytoplankton

Ecology

Phytoplankton are microscopic plants inhabiting the light-illuminated surface layers of the oceans. Marine Australian waters harbour tens of thousands different phytoplankton species which provide almost all of the marine primary production and so directly and indirectly support all higher trophic levels, e.g., small fish, prawns and other zooplankton, and shoreline filter-feeders such as mussels and oysters. Phytoplankton also play a central role in the global carbon, oxygen, and nutrient cycles, and produce half the oxygen on the planet.

Implications

Nutrient availability, temperature and stratification of the surface ocean are key determinants of phytoplankton abundance, community composition and production. Warm, stratified and nutrient-poor waters are dominated by small phytoplankton species and support long foodwebs with low fish production. By contrast, cool, well-mixed and nutrient-rich waters are dominated by large phytoplankton and support short foodwebs with high fish production. Of crucial importance for the state of the pelagic system will be how nutrient availability, itself driven by atmospheric and hydrodynamic processes, and anthropogenic activities will change.

On occasion, some phytoplankton species form large, colourful, and sometimes toxic harmful algal blooms (HABs). If such phytoplankton are filtered by shellfish, toxins accumulate in their tissues. Consumption of such shellfish can cause severe health problems or even death. Algal toxins can also accumulate in foodwebs and kill fish and other marine animals. Climate change is likely to alter the environmental conditions that affect the occurrence of HABs.

Projected climate change impacts	Recommendations
• Increasing SST and southward flow of the East Australian Current (EAC) will drive phytoplankton species southwards • Phytoplankton abundance already changing regionally in Australia, including HABs • Species with calcareous shells such as coccolithophores and foraminifera may decline in abundance • Earlier timing of the peak in production of some phytoplankton • Warming and increasing stratification will considerably alter phytoplankton community composition, e.g. the productive southeastern temperate phytoplankton province may shrink considerably in area • Changes in phytoplankton abundance, distribution, and timing of production are likely to drastically impact most marine life 	**Information gaps** • No knowledge of how the phytoplankton community has changed in the past or will change in the future in Australian waters **Monitoring and Modelling** • Only monitoring of phytoplankton in Australian shelf waters is by satellite (since 1997), i.e. phytoplankton abundance at ocean surface which does not inform about changes at species-level or below the surface • Need for phytoplankton monitoring along the EAC where dramatic changes in abundance, distribution and timing are expected • Coupling NPZ (nutrient-phytoplankton-zooplankton) models to hydrodynamic models will allow assessment of how primary production may change in the future **Building resilience to climate change:** • Reduce nutrient inputs to coastal zone • Reduce overfishing of pelagic foodwebs

6.2 Zooplankton

Ecology

Zooplankton are microscopic- to jellyfish-sized animals drifting in ocean currents and distributed throughout all marine environments. Zooplankton include species that spend all their time (their entire life cycles) in the plankton as well as the larval stages of a range of benthic and pelagic species. They are perhaps the most numerous multicellular group of animals in the sea, are the main secondary producers in the oceans, transferring energy from primary producers such as phytoplankton to higher trophic levels including fish, seabirds, turtles and whales. Thus directly and indirectly, they support all the world's fisheries and play a central role in the global carbon and nutrient cycles, removing large quantities of carbon from the surface layers of the ocean and distributing it to the deep-sea.

Implications

Because of their short generation times, zooplankton are sensitive sentinels of climate and environmental change. There is some evidence that the abundance of jellyfish (gelatinous zooplankton) in semi-enclosed coastal habitats have increased through human-induced stratification and nutrient inputs. Many zooplankton species and larval stages of coastal species such as mussels have calcium carbonate shells that are sensitive to dissolution in acidic waters. These may be under threat in the future due to rising acidity of the world's oceans. It is unknown whether humans are impacting zooplankton communities in Australian waters, as the longest extant zooplankton time series in Australia is only two to four years long and consists of a single cross-shelf transect. Much early zooplankton work remains unpublished.

Projected climate change impacts	Recommendations
• Large southward movements of tropical and temperate species as ocean waters warm • Changes in abundance of particular species with flow on effects to their prey and predators • Earlier timing of appearance with warming (ie. changes to reproduction/recruitment patterns and consequent changes to succession patterns in communities) • Changes in timing could lead to decreased coupling with lower trophic levels (phytoplankton) and reduce fish yields • Species with calcareous shells such as echinoderms, crustaceans and molluscs (especially pteropods) may not be able to maintain shell integrity in a more acidic ocean • Increased incidence of jellyfish swarms with warming oceans  	**Major Information gaps** • Need knowledge of how the secondary productivity of Australian waters, which supports almost all higher trophic levels including fish, seabirds, turtles and marine mammals, has changed in the past or will change in the future • Digitise historic data: Some earlier (pre-computer) zooplankton data remains unpublished/undigitised and unavailable **Monitoring and Modelling** • Urgent need for long-term monitoring of zooplankton along the EAC where dramatic changes in distribution and timing are likely to occur and where valuable fisheries exist. • Need to utilise zooplankton more effectively as environmental indicators • Couple NPZ (nutrient-phytoplankton-zooplankton) models to hydrodynamic models - this will enable an assessment of how secondary productivity may change **Building resilience to climate change** • Reduce overfishing of pelagic foodwebs • Reduce nutrient inputs into coastal zone

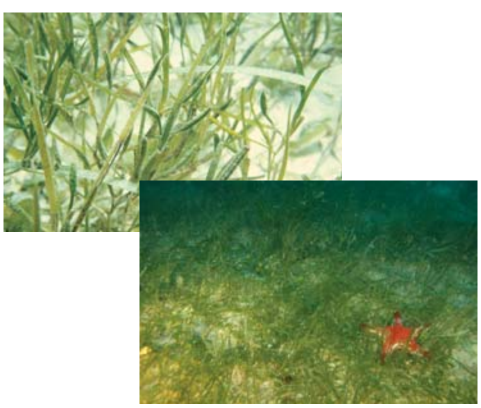
6.3 Seagrasses

Ecology

Seagrasses are found in shallow coastal waters all around the Australian coastline, and typically on soft sediments. Australia has the highest diversity of seagrasses and most extensive seagrass beds globally. Seagrass beds play a vital role in nutrient and carbon cycling and act as a buffer between the land and the sea. They also baffle water flow, trap sediments and filter coastal waters. Seagrass beds form important habitat for many species of fish and crustaceans including exploited species, so declines in seagrass cover are often detrimental to local economies. They also support internationally important populations of endangered species such as green turtles and dugongs.

Implications

Temperature and water clarity are the major factors controlling the biogeographic distributions of seagrasses in Australian waters. Large-scale declines of seagrass beds, both in Australia and globally have been attributed to a loss of water quality from increased land use and coastal development. Australia has lost extensive areas of seagrass habitat in the last 50 years. As seagrasses tend to be carbon limited, an increase in atmospheric CO_2 will lead to a higher proportion of dissolved CO_2 in ocean waters thus favouring seagrass productivity. However, the projected alterations in temperature, UV radiation and storm regimes may act to negate the benefits of increased CO_2. At present the greatest threat to seagrass beds is from non-climate anthropogenic pressures, which coupled with the extra stressors of a rapidly changing climate, threaten their persistence and resilience.

Projected climate change impacts	Recommendations
• Possible increases in seagrass biomass as CO_2 levels rise and enhancement of the role of seagrass in coastal carbon and nutrient cycling • Shifts in species distribution southwards and alteration of species composition of seagrass beds as temperatures warm • Alteration of frequency and timing of flower and seed production • Increase in seagrass bed destruction if storm regimes and river flood events become more frequent or more severe • Disappearance of UV intolerant species from shallow waters as UV radiation levels rise 	**Information gaps** • Need to improve knowledge of current distribution, abundance and community composition • Little understanding of links between seagrass and ecosystem functioning **Monitoring and Modelling** • Monitoring of seagrass bed health of indicators for stress • Modelling programmes, including bioclimatic models, will improve understanding of ecology and functioning **Building resilience to climate change** • Monitor and control coastal water quality • Reduce bottom trawling by fisheries within seagrass beds

6.4 Mangroves

Ecology

Mangrove communities are diverse assemblages of trees and shrubs that are found fringing much of the tropical and sub-tropical coastline of Australia in sheltered areas, with the most extensive communities found in the tropics. The mangrove flora of Australia is one of the most diverse globally and these are highly productive systems. Mangroves act as an important buffer between land and sea, filtering terrestrial discharge, decreasing sediment loading of coastal waters and maintaining the integrity of coastlines. They are also valuable for their role in nutrient and carbon cycling. Mangroves act as a nursery and breeding habitat for marine species such as fish, crabs and prawns, including many commercially valuable species, and they also support a variety of terrestrial species such as bird populations.

Implications

Mangroves are under threat from coastal development, river catchment modification and pollution. While adapted to cope with salty conditions, mangroves thrive in areas where there is plentiful input of fresh water. Sea level rise is now considered a major threat to mangroves; they grow on shorelines with a low profile, thus, a small rise in sea level could inundate large areas of mangroves. Increases in atmospheric CO_2 may enhance mangrove growth, but this will depend on other factors such as nutrient availability and salinity levels. Given the role of mangroves in coastal systems, conservation of mangroves should be considered a priority management strategy in response to climate change threats.

Projected climate change impacts	Recommendations
• Possible increase in mangrove productivity as atmospheric CO_2 levels rise • Destruction of mangroves with sea level rise and enhanced frequency or intensity of storms • Shift in species distributions with rising temperatures, depending on habitat availability and dispersal • Alteration to growth rates and survival with changes in rainfall pattern and abundance 	**Information gaps** • How mangroves will respond to syngergistic effects of various environmental changes • Links between mangroves and ecosystem functioning **Monitoring and Modelling** • Monitoring of mangrove vegetation, plankton and benthic fauna will warn if changes are occurring and inform understanding of mangrove vulnerability • Geomorphic and hydrodynamic modelling of coastlines with projected changes in sea-level will improve understanding of threat of sea level rise on mangroves **Building resilience to climate change** • Monitor and control coastal development and catchment modification that would impact mangroves • Initiate mangrove conservation and revegetation programmes

6.5 Kelp

Ecology

Kelp is the common name for large, brown, sub-tidal macroalgae that form surface or mid-water canopies over hard substrates in temperate regions. Kelp species comprise a small proportion of marine macroalgae, but they are the dominant foundation organisms in their habitats, and are thought of as bioindicators of the integrity of these temperate reef ecosystems. They can form large floating canopies up to 30 metres above the sea floor in the form of ‘kelp forests’. This habitat architecture is inhabited by diverse assemblages of animals and smaller seaweeds, and the primary production of kelp is also utilised by a broad community of organisms. Kelp species are distributed throughout the southern half of Australia wherever persistent hard substrate receives enough light. The distributions of some kelp species are limited to Tasmania or other particular areas such as the South-east and South-west Large Marine Domains.

Implications

The distributions of kelp species in Australia and elsewhere are shaped by temperature, nutrients, turbidity, light penetration, wave action and sand scour, and the relative prevalence of herbivores and their predators. Large declines of giant kelp and other macroalgae along the east coast of Tasmania in the last 50 years have been attributed to rising sea temperature, but deforestation, agriculture, urban development, and other land-use changes might have changed sedimentation and runoff characteristics decreasing the quality of kelp habitat in some settings. The removal of predators through fishing or the invasion of new herbivores, or both, might lead to kelp forest degradation as it has elsewhere throughout the world. One known example of herbivore (sea urchin) invasion of Tasmanian kelp forests is likely the result of climate change.

Projected climate change impacts	Recommendations
• Increasing temperatures and decreases in nutrients will shift the distributions of kelp and other temperate reef species southward imperilling some species due to the bounded southern coastline • Changes in storminess and physical disturbance regimes will shift the distributions and compositions of kelp ecosystems. • Changes in rainfall and watershed integrity will affect kelp habitat • A decrease in zonal westerly winds will inhibit eastern Tasmanian upwelling and a strengthening of the East Australia Current will limit impingement of nutrient rich southern waters • Unchecked outbreaks of herbivores might decimate remaining kelp forest stands in some areas • UV-related reductions in photosynthesis, growth, and re-cruitment may become less im-portant with projected in-crease in stratospheric ozone concentrations 	**Information gaps** • Much, though not all, of the information used to develop these projected impacts are from elsewhere throughout the world. Much more knowledge about Australian kelp ecosystems is needed **Monitoring and Modelling** • Only one reasonably useful time series was identified, but kelp and other macroalgae are relatively easy to monitor and should be sensitive to climate change making them a very good candidate for monitoring. This is especially true because surface seawater temperature is a major determinant of macroalgal geographical distributions **Building resilience to climate change** • Protect catchments and manage coastal development to reduce sediment and nutrient inputs into the coastal zone • Prevent overfishing of kelp forest predators and herbivores in marine ecosystems

6.6 Rocky shores

Ecology

Rocky shores are one of the most easily accessible marine habitats and are a transition zone between the land and sea. The rocky shorelines of southern Australia contain very high numbers of endemic species; it has been estimated over 90% of mollusc and echinoderm species and 60% of seaweeds may be endemic.

Implications

Many animals and plants in the rocky intertidal such as barnacles, limpets and seaweeds, are sessile as adults and can be quickly and easily surveyed using non-destructive methods. The rocky intertidal has a long history as a test area for important concepts in ecology and a good knowledge of processes and species biology exists for many Northern Hemisphere shores and for limited parts of the Australian coastline. Some of the best and most numerous examples globally of marine range shifts with warming temperatures have come from rocky shore surveys. Further, monitoring programmes for climate change impacts have been initiated in the UK, USA and other countries. The rocky intertidal provides an ideal sentinel system to monitor climate change in a cost effective manner.

Projected climate change impacts	Recommendations
• Large southward movements of tropical and temperate species. Evidence of such shifts is already apparent from many rocky shores outside Australia • Changes in abundance and community composition • Alteration of peak timing of events such as reproduction and larval or spore release and changes in reproductive output  	**Information gaps** • Limited knowledge of rocky shore species distributions, abundance and ecology along much of the southern Australian coastline with many potentially new species yet unrecorded and their interactions unknown **Monitoring and Modelling** • Large-scale baseline surveys using techniques such as digital photography are a cost-effective method to provide a sound database against which to measure change • Modelling techniques such as climate envelope models or more mechanistic dispersal models will allow prediction of potential impacts of climate change **Building resilience to climate change:** • Control coastal development and building of seawalls etc. • Reduce anthropogenic inputs into the coastal zone • Create protected areas where collection of animals and plants is prohibited and trampling etc. discouraged

6.7 Tropical corals

Ecology

Tropical coral reefs are composed of hermatypic corals (cnidaria, especially scleractinia and hydroids) containing microscopic symbiotic algae (zooxanthella) that together form the carbonate substrate on which the reef ecosystems are based. Much of Australia's northern shores along both east and west coasts are lined by extensive coral reef ecosystems. Globally, coral reefs are estimated to house between one and nine million species, of which less than 10% are known to science. In Australia, 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. This biodiversity is potentially important as a storehouse of genetic material, but it is also an attractive feature of such reefs as the Great Barrier and Ningaloo Reefs. The rich ecosystems of coral reefs depend on the myriad of interactions and functional groups to provide an inherent resilience to the effects of disturbance events.

Implications

Coral reefs are critical to Australia's economic well-being: as well as providing resources and habitat for commercially important fish and crustacean species, they are the basis for Australia's tourist industry generating $5 billion in tourism alone per annum. They also play a critical role in coastal protection, moderating the impacts of waves on our coasts. Water quality and overfishing are thought to be the primary near-term threats to Australian coral reefs, but now they face growing risks from climate change.

Projected climate change impacts	Recommendations
• Based on current coral physiology, a 1-2°C warming will lead to annual bleaching and regular large-scale mortality events. Already, warming over last 30 years has led to repeated coral bleaching events, with the reefs in NW Australia most sensitive • Ocean acidification will tip balance from coral calcification to erosion; atmospheric CO_2 that exceeds 500 ppm will severely compromise corals • Southward expansion of tropical reef communities will be limited to several hundred kms south because of decreased carbonate concentrations further south. Habitat quality may limit this expansion more strongly. 	**Information gaps** • Understanding the adaptive capability of corals to cope with warming seas and rising acidity **Monitoring and Modelling** • Modelling is needed to assess the relative impacts on corals of increased storm activity, sea level rise, ocean warming, acidification and overfishing on coral reef integrity **Building resilience to climate change** • Changes in storm activity and runoff, and sea level rise are likely to act synergistically with increasing temperature and acidification to reduce coral viability. Global reductions in CO_2 emissions are required to minimise these impacts • Reducing sediment load and nutrient inputs • Eliminate overfishing of herbivorous fish grazers on coral reefs

6.8 Cold water corals

Ecology

Cold water corals are known from seamounts and the continental rise off southern Australia, particularly within the Tasmanian Seamounts Marine Reserve, as well as from seamounts in Australian territorial waters around Norfolk Island. These corals are found to depths of several hundred meters below sea-level. The reefs and carbonate mounds formed by cold water corals are considered 'hotspots' of biodiversity, comparable to shallow-water tropical reefs. The occurence of these important habitats is a very recent discovery in the southern hemisphere. Over 850 macro- and megafaunal species were recently found on seamounts in the Tasman and southeast Coral Seas of which 29-34% were new to science and are potential endemics. However, very little is known of the population dynamics or ecosystem functioning of cold water corals or even their distribution in Australian marine waters.

Implications

Bottom trawling by fisheries, seabed mining and ocean acidification are considered major threats. Cold water corals are slow-growing and reefs can take many thousands of years to develop. The global distribution of cold water corals appears to be influenced by the depth of the aragonite saturation horizon, below which the corals have difficulty laying down a skeletal matrix. The depth of the aragonite saturation horizon is projected to decrease as climate changes; it is estimated that ~70% of cold water coral reefs globally will be affected by 2100. Seamount habitats off southern Australia may become inhospitable to cold water corals below a few hundred metres depth and the resulting loss to Australian marine biodiversity will be high.

Projected climate change impacts	Recommendations
• Disappearance of cold water corals from deeper areas as the depth of the aragonite saturation horizon becomes shallower • Alteration of surface water plankton productivity may have implications for the food supply to suspension-feeding cold water corals 	**Information gaps** • Very little knowledge on occurrence and connectivity of coldwater corals and associated fauna in Australian waters. • Little knowledge on links between cold water corals and ecosystem function **Monitoring and Modelling** • Performance monitoring (e.g. repeated video observations of fixed sites) of the Tasmanian Seamounts Marine Reserve (TSMR) • Low frequency monitoring would show rates of recovery following cessation of trawling as well as detecting effects of changes in aragonite saturation state **Building resilience to climate change** • Reduce bottom trawling on seamounts and other areas where cold-water corals occur • Strict control of seabed activities such as mining and gas exploration in cold water coral areas

6.9 Soft sediment fauna

Ecology

Soft sediment invertebrate fauna such as crabs, bivalves, prawns and worms cover a broad spectrum of sizes and life habits. These invertebrate assemblages are extremely diverse and abundant because of the diversity of soft sediment habitats and because these habitats cover the vast majority of the area of Australia's marine environment. Furthermore, a very high proportion of the species inhabiting these habitats remain un-described in Australia. This fauna recycles a considerable portion of the overall energy in marine systems that would otherwise be lost. To a very large extent, they support and mediate the production and maintenance of Australia's marine ecosystems thereby supporting the Australian economy and society through ecological stabilisation, fisheries production, pollution mitigation, and other services.

Implications

Australia's soft sediment communities are sensitive to changes in production in the overlying water column and to changes in adjacent coastal systems that affect production or sedimentation or cause organic enrichment or other pollution. Seafloor trawling considerably modifies the structure and functions of soft sediment ecosystems that are heavily fished, but other non-climate related human impacts are usually local. Because of the very high proportion of trophic flows mediated by soft sediment invertebrate fauna, both destructive fishing and climate change will impact fish and other valued vertebrate populations throughout Australian marine ecosystems. The management of fishing and pollution is thus a climate change adaptation strategy because these manageable stressors decrease resilience to climate change.

Projected climate change impacts	Recommendations
• Soft sediment fauna is expected to be sensitive to several manifestations of climate change including warming, decreases in ocean pH, changes in primary production, hydrology, storminess and extreme weather events • Warming will shift the ranges and distributions of many species of soft sediment fauna differentially leading to new assemblages of organisms • Acidification will erode the shells of molluscs, corals, benthic foraminifera, and other groups with carbonate shells. • Changes in water column primary production will alter abundances, community interactions, and benthic-pelagic coupling • Changes in prevailing current dynamics will affect soft sediment systems considerably • Changes in freshwater input will modify the benthic community over vast areas 	**Information gaps** • Despite the fundamental importance of soft sediment invertebrate fauna, there are no observed impacts of climate change on this group in Australia because of the paucity of sampling, taxonomic knowledge and analysis • Distinguishing climate impacts from fishing impacts such as sea floor trawling will be a profitable area of research because soft sediment communities are a good model system **Monitoring and Modelling** • Several characteristics make soft sediment invertebrate fauna useful sentinels in monitoring and modelling. These include its sensitivity to climate change, ease of sampling, importance to most Australian fisheries, and its known coupling with overlying communities **Building resilience to climate change** • Protect the integrity of soft bottom ecosystems by preserving some areas and regulating disturbance in others • Address coastal watershed modification and pollution problems

6.10 Benthic and demersal fishes

Ecology

The benthic and demersal fishes of Australia include all fish species that live on or near the ocean floor. This fauna is extremely diverse and endemic by world standards due to a convergence of high tropical diversity and the isolation of the southern temperate regions. Much of the energy and nutrients in Australia's marine domain flows from water-column and sea floor production sources to fish species with benthic and demersal lifestyles. Accordingly, this fish fauna plays a key role in shaping most aspects of Australia's marine biological communities through predation on secondary producers, as prey and forage for other biota, and through bioturbation. These species provide tremendous social and economic services as targets for commercial and recreational fisheries.

Implications

The fishing pressure on Australia's commercially important benthic and demersal fish stocks is substantial in many regions. Eight of the 17 stocks listed as overfished in the Australian Bureau of Resource Sciences 2004 annual report on the state of Australia's fisheries are in the south-east demersal fishery group. The effect of fishing is presumably so important that assessments and projections of climate change impacts should not be conducted without considering the impacts of fishing in the area of interest. Pollution should also be considered a stressor that reduces the resilience of benthic and demersal fish assemblages to climate changes.

Projected climate change impacts	**Recommendations**
• Benthic and demersal fish species will keep shifting south, most prominently in the eastern and southeastern regions • Some populations may decline where ranges are bounded to the south • Continued decreases in the zonal west winds are likely to lead to continued depletions and potential stock collapses • Changes in temperatures, current patterns, and primary and secondary production may affect larval fish health and transport thereby influencing recruitment potential • Ultraviolet radiation may adversely affect larval fish development and survival • Climate change impacts will potentially combine with fishery impacts to exacerbate further depletion of groundfish stocks 	**Information gaps** • Although demersal fish stocks are of great commercial interest, information about range shifts and other impacts in Australia are mostly anecdotal • Little is known about the combined effects of fisheries and climate change impacts and associated trade-offs **Monitoring and Modelling** • Explicit and quantitative information needed on climate change effects on demersal fishes and their larval stages • The wealth of biological and fisheries information that does exist is useful for designing informative monitoring and modelling studies on targeted species **Building resilience to climate change** • Protect the resilience of benthic and demersal fish populations by adopting appropriate and adaptive management practices that regulate overfishing, bycatch problems and destructive fishing • Address coastal watershed modification and pollution problems

6.11 Pelagic fishes

Ecology

Pelagic fishes occupy the largest ecosystem on the planet, the surface and water column of the open ocean. There are about 200 pelagic fish species around Australia, and while the most obvious members are the apex predators such as tunas, billfish and sharks, the mid-trophic level pelagic species, such as sardines, anchovies, and squids, are also important as food for larger marine animals. The majority of species are widely distributed: for example swordfish are found worldwide.

Implications

The tunas and billfish are valuable species economically and socially, representing high value to both commercial and recreational fishers in Australia. The expected impacts of climate change will be seen first on the distribution and abundance of pelagic species. Around Australia, the range of many species will expand to the south as the ocean warms. For pelagic species living near regions of coastal upwelling, such as sardines, mackerel and redbait, increases in upwelling favourable winds may lead to increased local productivity, and benefit these species and their predators. However, the general intensification of stratification may reduce the productivity of pelagic fish on the broader scale.

<table>
<tr><th>Projected climate change impacts</th><th>Recommendations</th></tr>
<tr><td>

Ocean warming will result in species moving southwards
Changes in abundance of particular species in local regions is likely
Increases in wind that affect upwelling intensity may benefit the mid-trophic level pelagic species locally, such as anchovies
Changes in temperatures, current patterns, and primary and secondary production may affect larval fish health and transport thereby influencing recruitment potential
Ultraviolet radiation may adversely affect larval fish development and survival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Information gaps

Most information comes from fishery data, and thus is limited to where fishers go fishing. Fishery-independent information on distribution and habitat preferences of the majority of large pelagic fishes, sharks and squids is required

Monitoring and Modelling

Electronic tagging for large indicator species, such as tuna and sharks; acoustic surveys for mid-trophic level species such as sardines, anchovies and meso-pelagic fishes
Habitat preference models that can be forced with climate change scenarios are needed. Bioclimatic modelling is one such approach

Building resilience to climate change

Improved management of target species especially for shared stocks
Minimise bycatch of pelagic sharks and billfish


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6.12 Marine turtles

Ecology

Of the seven living species of marine turtles, six are found in Australian waters and all of these are considered globally endangered. These nest on tropical and subtropical sandy beaches around Australia. Flatback turtles nest only on Australian beaches and so can be considered as endemic to Australia. Adult turtles exhibit site fidelity to feeding and breeding grounds. All marine turtles undertake extensive migrations during their life cycle, except flatbacks which remain in or near coastal waters for all their life.

Implications

Marine turtles are highly valued by coastal indigenous communities for their spiritual and cultural significance and also benefit local economies through ecotourism. Climate change is likely to be a major threat to marine turtles given their life history characteristics, such as slow growth rate, and as all stages of their life histories are strongly influenced by temperature. In particular, gender of embryos is determined by ambient nest temperatures and small increases in temperature may strongly bias the sex ratio of hatchlings towards females. Climate-induced changes in food resources in critical habitats will also have a major impact on marine turtle populations. Fisheries (high numbers of turtles are taken as bycatch), coastal development and habitat loss, marine debris and pollution are also major threats to marine turtle populations.

Projected climate change impacts	Recommendations
• Skewing of sex ratio towards females as temperatures rise • Climate-induced alteration of food supplies will impact turtle populations • Climate-related increases in wave energy and storm events may erode nesting beaches and reduce egg survival • Range expansions may occur with turtles occurring further south (in Southern Hemisphere) as temperatures rise • Alteration of peak timing of egg laying already observed in Florida for loggerhead turtles 	**Information gaps** • Limited knowledge of juvenile pelagic stage and adult dispersals • Limited knowledge of main causes of mortality in Australian stocks **Monitoring and Modelling** • Turtle tagging and tracking programmes will inform on dispersal and population connectivity • Population modelling techniques will inform on potential impacts of climate change on turtle populations **Building resilience to climate change:** • Reduce bycatch of marine turtles in fisheries • Control coastal development and protect nesting beaches • Reduce marine debris and pollution, including plastics

6.13 Seabirds

Ecology

Seabirds are birds adapted to life in the marine environment. Most species nest in colonies varying in size from a few dozen to many millions of individuals. They occur around Australia, and feed both at the ocean's surface and below it. Seabirds can be highly pelagic, coastal, or spend a part of the year away from the sea entirely. Many also undertake long annual migrations. A diverse seabird fauna breeds on mainland and island coastlines around Australia. The world's largest colony of crested terns occurs in the Gulf of Carpentaria in Australia's north, and almost a quarter of all albatross species have nesting sites on islands around Tasmania and on Macquarie Island. Planktivorous seabirds nesting in Australia are found only in the southern waters but can occur in high numbers. For example, an estimated 23 million short-tailed shearwaters nest in south-east Australia every year.

Implications

Some species of seabirds are highly valued by coastal indigenous communities for their cultural and spiritual significance and may also be hunted for food. They also benefit local economies through ecotourism; colonies of little penguins on Phillip Island near Melbourne bring in millions of dollars annually for local communities. Seabirds are efficient integrators of ecosystem health, as many feed on small pelagic fish and zooplankton and thus are sensitive to changes at lower trophic levels. There is some controversy regarding the extent that seabirds remove exploited fish species and compete with fishers.

Projected climate change impacts	Recommendations
• Warming will expand or shift distributions southwards. Already evidence of distributional changes in tropical Australian seabird populations • Altered reproductive success. Breeding success related to SST in some Australian seabirds • Nesting may occur earlier. Earlier laying already recorded in some Australian seabird populations • Nesting and feeding habitats lost or altered as sea levels rise and storm intensity increases • Alteration of currents will impact on distributions, migration and foraging 	**Information gaps** • How food resources will change • Limited knowledge on distributions and feeding of many species outside of breeding season **Monitoring and Modelling** • Models of the productivity of lower trophic levels (plankton and small pelagic fish) are essential for forecasting future changes in seabird populations • Breeding success data provides valuable information on ocean productivity • Timing of egg laying as an indicator of changes in phenology **Building resilience to climate change** • Avoid overfishing of small pelagic fish that are a major food source for seabirds • Ensure productivity of lower plankton trophic levels, which is both a direct and indirect food source for seabirds, is maintained • Ensure fishing practices minimise seabird mortality • Maintain the integrity of the intertidal zone, which provides valuable food resources for wading shorebirds

7. GENERAL FINDINGS AND COMMON ISSUES

Three general findings emerged from this study:

- First, although particular factors such as temperature stand out as prominent drivers of observed changes in Australia's marine flora and fauna, it is the combined effects of multiple climate and oceanographic factors that will shape Australia's marine life in the future.

- Second, Australia's marine life is currently affected strongly by non-climate related stressors such as fisheries, coastal runoff and pollution, and the ecological effects of these stressors will serve to reduce ecosystem resilience to climate change. An integrated and adaptive management approach is required to deal with these combined effects.

- Third, both monitoring time series data and modelling of climate change impacts in Australia's marine ecosystems are extremely limited at present, and represent crucial components of a strategic national assessment of climate change impacts so that intelligent policies and management strategies can be developed.

This report highlights climate change impacts that have been observed or might be expected in Australia, but it is important to note that extrapolations of observed changes from studies in Australia or elsewhere represent our best current knowledge and thus have associated uncertainties. This is because of the uncertainties in climatic and oceanographic responses to climate change, and the complexity of the biological and ecological responses. This includes the possibility of non-linear and threshold effects in biological and ecological communities that can cause catastrophic collapses or shifts to alternate (often degraded) stable states. Knowledge of the conditions that lead to these thresholds may be a crucial aspect of effective management and adaptation strategies of the future. Research to gain such knowledge should focus on the various ecological, exploitation and degradation contexts in which climate impacts may manifest because theory suggests that non-climate stressors can change the resilience landscape on which climate changes affect biological systems.

The conspicuous roadblock to predicting the effects of climate change on marine life in the face of such uncertainties in Australia is the current lack of a strategic programme that includes a combination of monitoring and modelling potential impacts. Without this, we cannot progress far beyond the conclusion that climate impacts are occurring in Australia, and that some of the impacts might prove severe. Concommitently, we will be unable to predict the full character, magnitude, and the breadth of community and ecological impacts and implications.

A summary of the severity of the impacts of climate change on Australian marine life expected this century is provided in Table 7-1. These ratings are based on the expected responses of each group to predicted changes in temperature, salinity, wind, mixed layer depth, pH and sea level, as described in the Technical Report (Part B), and from information gathered in the Literature Review (Part C). The implicit assumption underlying Table 7-1 is that Australian marine species will respond in similar ways to their counterparts in other areas throughout the world; very little of the information used to generate this table is from local species or waters. Effects are grouped into four broad categories:

(1) Effects on distribution and abundance – species are generally expected to move toward the poles with warming; species with calcium carbonate shells are likely to decline in abundance;

(2) Effects on phenology or timing of life cycle events – the timing of blooms and migrations are expected to occur earlier with warming;

(3) Effects on physiology, morphology, and behaviour – environmental change will directly affect rates of metabolism, reproduction, development, photosynthesis and respiration;

(4) Impacts on biological communities – this is dependent upon the magnitude of the response and the importance of the group to ecosystem functioning.

A number of features with respect to climate change impacts are evident from this table. First, the most affected marine groups are likely to be tropical coral reefs, cold water coral reefs, rocky reefs and kelps, phyto- and zooplankton, and benthic and demersal fish. This may partially reflect where the best knowledge is available locally or overseas. Second, largest climate impacts are likely to be on biological communities more generally. This is because much of the marine organisms that are going to be highly impacted are foundation species or species that form the base of the open ocean foodweb. Last, it appears that distribution and physiology are generally more likely to be affected than phenology. This should be interpreted with caution, however, as it is far easier to collect data on changes in distribution from the field and data on physiological responses in the laboratory than to measure changes in phenology. One conspicuous lesson from this summary and from this exercise overall is that information on Australian marine impacts of climate change is extremely sparse. More quality empirical information is needed about the potential effects of climate change on Australia's marine ecosystems, and this information needs to be collected strategically in the context of innovative analytical approaches such as integrative ecosystem models.

Table 7-1: Expected impact of climate change on Australian marine life in terms of the four potential biological responses to climate impacts. These ratings are based on the expected response to predicted changes in SST, salinity, wind, pH, mixed layer depth, and sea level, as described in the specific sections.

Groups	Distribution / abundance	Phenology	Physiology/ morphology / behaviour	Impacts on biological communities	Example impact	Recommendations
Phytoplankton	High	High	Medium	High	Temperate phytoplankton province will shrink considerably	• Instigate a programme to monitor changes of phytoplankton along the East Australia Current • Develop coupled NPZ (nutrient-phytoplankton-zooplankton) and hydrodynamic models to assess how primary productivity will change in the future
Zooplankton	High	High	Medium	High	Acidification will dissolve planktonic molluscs	• Establish long-term monitoring of zooplankton along the East Australia Current • Couple NPZ models to hydrodynamic models to detect change
Seagrasses	Medium	Low	High	Medium	Increased dissolved CO_2 may increase productivity	• Support/initiate large-scale monitoring programmes • Bioclimatic models are quick and cost-effective method to improve understanding of distribution and potential alteration with climate change
Mangroves	Medium	Low	Medium	High	Sea level rise will destroy mangrove habitat	• Mangrove conservation should be a priority to mitigate climate change impacts on coasts and coastal communities. • Geomorphic modelling of coastlines with sea-level change projections
Kelp	High	Medium	High	High	Ranges will shift southwards as SST warms	• Establish macroalgal assessment and monitoring studies • Minimise impacts of pollution and overfishing in kelp areas
Rocky reefs	High	Medium	High	Low	Species ranges will shift southwards as temperatures warm	• Instigate a programme to monitor species identified as 'indicators' of climate change • Develop models to assess how rocky shore communities will change in the future
Coral reefs	High	Medium	High	High	Acidification and warming will cause calcification problems and coral bleaching	• Ecosystem models needed to evaluate the relative importance of the various stressors and impacts on coral reef ecosystems • Reduce watershed modification / pollution impacts and fisheriers impacts to increase resiliency
Cold water corals	High	Low	Low	High	Ocean acidification will dissolve reefs	• Map and describe physical and biological characteristics • Monitor corals (e.g. in Tasman Seamount Reserve), thus learning about recovery rates, dynamics, and effects of climate change
Soft bottom	Medium	Medium	Medium	Medium	Modified plankton	• Integrate and couple benthic monitoring (infauna and epifauna) into

Groups	Distribution / abundance	Phenology	Physiology/ morphology / behaviour	Impacts on biological communities	Example impact	Recommendations
fauna					communities or productivity will reduce benthic secondary production	the monitoring of overlying plankton for climate impacts • Employ ecosystem models to distinguish climate change impacts from fisheries impacts.
Benthic and demersal fishes	High	Medium	Medium	High	Southward movement of species along the east and west coast of Australia	• Design monitoring integrated with fisheries stock assessments and other available information from fisheries studies • Protect the resilience of fish populations by regulating overfishing, destructive fishing, and by restoring watersheds
Pelagic fishes	Medium	Low	Medium	Low	Pelagic tunas will move south with warming	• Electronic tagging of indicator species, such as tuna and sharks, to develop habitat preference models • Development of coupled NPZ-hydrodynamic models to predict productivity; linking physics to distribution and abundance
Turtles	High	Medium	High	Low	Warming will skew turtle sex ratios	• Monitor and protect critical habitats including nesting beaches • Support or initiate monitoring of key stocks in Australia and turtle tagging programmes and initiate modelling studies to help identify key causes of mortality and potential impacts of climate change
Seabirds	Medium	Medium	Low	Low	Shift in timing of peak breeding season as temperatures warm	• Monitor seabird abundances at key rookeries while accounting for other mortality such as introduced predators • Models of lower trophic levels are needed to forecast future changes in seabird populations
Total number of high impact habitats or species groups	**8**	**2**	**5**	**7**	High impacts are expected for distribution, physiology, and community processes	**General recommendations** • Choose ecological indicators of climate change that can be tracked using strategically planned monitoring programmes • Develop and implement integrated ecosystem models in coordination with monitoring to predict climate impacts

8. STRATEGIC DIRECTIONS FOR POLICY AND MANAGEMENT

We suggest two complementary strategies for minimising climate change impacts and adapting to these changes. First, it is in Australia's interest, economically and as stewards of a unique marine biodiversity, to help find global solutions to the global problem of greenhouse gas emissions. Second, local and regional strategies that protect or increase the resilience of Australia's marine ecosystems will help to minimise the overall impacts of climate change.

Because the direct impacts of climate change on Australian marine ecosystems are driven by global-scale changes in the Earth's atmosphere, climate and oceanography, approaches to ameliorating long-term impacts necessarily include global diplomacy and policy formulation. The very long lag times and equilibration dynamics of the atmosphere and ocean imply that some impacts are inevitable. Nevertheless, progress in global emissions policies may prove crucial for ultimately minimising the wholesale collapse of some Australian marine ecosystems and their associated industries.

Ecosystems are resilient to environmental disturbances and variability largely because the species constituting biological communities have adapted to various levels of natural disturbance and variability over evolutionary time scales. Rapid shifts in these disturbance regimes increase stress to these systems and decrease the overall resilience of the system to other disturbances. This well-developed principle portends greater climate change impacts to already stressed marine ecosystems than can be predicted by examining climate change effects in isolation and this idea underpins our vulnerability assessment. However, the resilience principle also implies that reductions of the stressors that humans can control may partially ameliorate increasing climate change impacts. Thus, easing the impacts of fisheries, pollution, habitat destruction, and other human impacts on marine ecosystems may be our best management option for marine climate change impacts in the near future and over local and regional scales. In principle, an immediate policy strategy for adapting to climate change impacts on marine ecosystems will include fishery and pollution management systems that are adaptive to climate change impacts. However, without quality monitoring and modelling programs, such integrated management strategies are not likely to be effective, nor would the effectiveness of any such adaptation efforts be measurable.

The resilience principle should hold true for most ecosystems and groups examined here, and kelp forests provide a clear example. These systems are resilient to environmental variability and disturbances when they are relatively intact. However, many Tasmanian kelp forest systems are severely over-fished and thus stressed, for example, by over-abundances of some herbivorous species that were previously controlled by natural predators and that have adverse impacts on the kelp itself. Kelp forests are also adversely affected by coastal pollution and eutrophication associated with watershed degradation and coastal development. Marine protected areas in Tasmania have provided a solution to enhance integrity of these ecosystems and thus their resilience to disturbances and stressors such as those associated with climate change.

Strategies to address these non-climate-related stressors are clearly workable for adapting to climate change impacts because they ameliorate the adverse effects of climate change by increasing the reslience of this ecosystem. Each of these separate management settings should be adaptive to climate impacts and integrated with national and state climate change management strategies by making allowances, or 'resource allocations', for climate change adaptation as part of the price for the privilege of exploiting public resources. For example, in addition to establishing marine protected areas, fishery managers could allocate 'climate change' portions of overall catch quota, thus reducing the catch quotas given to fishing participants. These impending costs to fisheries are well illustrated by the work of Lyne and his colleagues (2003) who conservatively projected that the expected increases in Australian ocean temperatures would have a 35% overall economic impact on Australian fisheries by 2070, and that temperate Australian fisheries will be more vulnerable than tropical ones. For example, they projected the economic impacts on Tasmanian, Victorian, and Western Australian fisheries to be 64%, 40%, and 38%, respectively, by 2070, assuming optimistically that fishing effort is managed well. What has not been examined is the extent to which the ultimate costs to the industry, society aand the ecosystem will hinge on management strategies.

The gemfish fishery, already under pressure from apparent over-fishing (like many of the south-east stocks), collapsed altogether when the zonal winds declined to their low point in the 10-year cycle (1989). In fact, the zonal winds in this year were at the lowest levels ever reported. Since then, the winds have fallen further, perhaps reflecting the predicted onset of overall weak zonal winds in the south-east region due to climate change, and also perhaps explaining why, despite the fishery being closed, there has been little or no sign of recovery of the eastern gemfish stock (Caton and McLoughlin 2004). Climate change impacts are already occurring and so climate change adaptation and allocation should be firmly established in Australian fishery management systems, especially in areas particularly vulnerable to climate change impacts such as the South-east Domain.

Coastal watershed managers will be faced with parallel management challenges as the link between coastal watershed health and nearshore marine ecosystem resilience to climate change becomes clearer. For example, in tropical New Caledonia, Wantièz et al. (1996) found the biomass of fish to be negatively associated with both temperature and rainfall, indicating that warmer and wetter climate would decrease fish biomass. Increased rainfall could adversely impact fishes by increasing turbidity, sedimentation, and nutrient input, and decreasing light penetration to the seafloor, thereby changing several attributes of fish habitat and food resources. The degradation of coral reefs, or the initiation of phase shifts from corals to fleshy algae, has profound effects on fish assemblages. Important fish nursery habitat such as estuaries, mangroves and seagrass meadows can be degraded by changes in rainfall, runoff and salinity. This might strongly affect early life history stages and recruitment, as well as transport of young fishes to offshore shelf and slope habitats. In addition, the biology of marine turtles is sensitive to subtle changes in the characteristics of nesting beaches and its other habitats. Examples such as these make it clear that watershed managers need to be included in management and policy initiatives for climate change adaptation and fisheries strategic planning, and that management should be developed to help protect and restore vulnerable species or habitats.

The need for such integrated management systems reflects the unavoidable trade-offs between different uses of Australia's marine ecosystems. A valuable modelling approach would be to integrate analysis of the impacts that each type of stressor (e.g. fishing, pollution, eutrophication, and climate change impacts) has on the economic and ecological value of goods and services of the marine environment in terms of potential costs that each stressor has on each other ecosystem use or value. This would enable an assessment to optimise strategies of resource utilisation in the context of climate impacts and the need for adaptation. Such trade-offs and the need for integrative adaptive management are reflected in this report by non-climate change related dimensions of vulnerability in the vulnerability assessment, which is described in the Technical Report (Part B), and by related examples of stressors that emerged during the Literature Review (Part C).

9. RECOMMENDATIONS FOR FUTURE RESEARCH

A clear research agenda on marine climate change impacts is needed for Australia so that the potential effects on Australia's marine life and associated ecosystem services to humans can be estimated with some degree of confidence. A national strategic research programme on marine climate impacts should combine and integrate strategic monitoring (of indicator species, groups, and ecosystems) and experimental approaches to assessment and adaptation (such as marine protected areas integrated management) with innovative modelling of climate impacts to develop capacities for prediction and adaptive management. The usefulness of predictions emerging from models will be very limited if they are not designed in parallel with high quality and strategic monitoring programmes that track key indicators that are central to the structures and functions of the ecosystems.

In this report we have identified six key questions that need to be addressed to better predict the impacts of climate change on marine species and habitats.

Key questions

1. How will the distribution and abundance of marine species and communities alter with climate change?

2. Which species are candidate bio-indicators for impacts of climate change?

3. Within large marine domains, where are sensitive areas or hotspots?

4. How will ocean productivity alter with climate change?

5. How would reduction in non-climate related stressors increase ecosystem resilience to climate change?

6. To what extent will marine climate change impacts affect socially and economically important uses of Australian marine ecosystems?

Modelling and monitoring recommendations for individual groups are detailed in Table 7-1. Here we have synthesised those recommendations into a blueprint for priority research.

Modelling

Modelling approaches are invaluable for predicting the likely future effects of climate change and other stressors on marine communities, and on interactions between community members. Approaches that can be applied in the short- to medium-term are the most useful at this juncture. Predictions from models give policy makers and regional planners confidence to implement or change current policy. We list four categories of models that would address the key questions:

- *Bioclimate envelopes (addresses Questions 1, 2 and 3).* These are a good broad-scale approach for studying marine climate impacts, and can be applied to many Australian marine species immediately. This approach is straightforward and is a good first approximation to the future distribution and abundance of marine species under climate scenarios. Well-studied groups such as fish, mangroves, seagrasses, seabirds, turtles and marine mammals should be the initial foci. Output from this approach will be easily interpretable in terms of present and future distribution maps of marine fauna and flora in Australian waters, which will be an invaluable tool for conservation managers and policy makers. This will enable identification of sensitive species useful as indicators of climate change and areas or "hot spots" where climate impacts are likely to be most severe. To deliver more robust predictions, bioclimate envelope models can be coupled with mechanistic models that incorporate some process understanding where sufficient data are available.

- *Mass-balance ecosystem models (addresses Questions 1, 5, and 6)*. These ecosystem models will provide predictions of future abundances of various species and functional groups in the context of whole interacting food webs, and they can be structured to focus on any particular question or biological components of food webs and ecosystems. Models such as Ecopath in combination with Ecosim and Ecospace are well-established and are particularly suited to the development of intelligent and adaptive marine resource management strategies, and for distinguishing the effects of non-climate related stressors (e.g., fisheries) from environmental variability and climate change. These trophodynamic 'Ecoclim' models have been constructed for several regions in Australia for ecosystem-based management of fisheries and other purposes, and could be brought together and forced by output from global climate models. Associated Ecospace models are a very good approach to inform the positioning of Marine Protected Areas and to estimate their ecological, social, and economic impacts.

- *NPZ models (addresses Questions 3, 4, and 6)* . These are the best models to forecast the productivity of the lower trophic levels in Australian waters in the future. This information is needed to understand climate impacts higher up the foodweb on pelagic fish, seabirds, many marine mammals, soft-bottom benthic invertebrates, and demersal fish. These models would enable assessment of the economic implications of climate change for the fishing industry, especially when implemented in parallel with trophodynamic ecosystem models such as Ecopath. Additionally, NPZ models are also a very good approach to inform the positioning of offshore Marine Protected Areas.

- *Population dynamics models (addresses Questions 2, 5, 6).* These models capture species dynamics, and when forced with climate change scenarios. Such models should be implemented on well-studied species that we know are particularly sensitive to climate change. Candidate groups fitting these criteria include tropical corals (sensitive to ocean warming and acidification), seagrasses and mangroves (sensitive to sea level rise). These groups are also critical foundation species and are important for coastal defence. Other groups include marine turtles where the sex ratio of hatchlings depends on nest temperature, and harmful algal blooms and jellyfish such as *Irukanji* and bluebottles, which can increase in abundance with warmer temperatures and stratification. Many well-established fisheries models can be adapted to incorporate processes influenced by climate change and can be used for exploited and non-exploited stocks. Realistic population dynamic models are -suited for adaptive management and for exploring the effects of non-climate related stressors, especially when used in combination with multi-species models.

Monitoring

Long-term baselines are crucial for documenting and understanding response of species and ecosystems to climate change. Australian marine scientists have long claimed that the lack of observable climate signals is a consequence of the paucity of time series in the region particularly for groups such as zooplankton, a well-recognised sentinel of change. Our summary of existing time series confirms that there are very few long-term baselines; there are virtually no time series longer than 10 years in Australia except for tropical corals and possibly marine turtles, cetaceans and seabirds. Without such datasets, attribution of climate change impacts will be severely compromised.

Models are extremely valuable for forecasting and to underpin adaptive management decisions, but they do not represent reality. To provide definitive answers to the key questions identified, it is necessary to have a robust and targeted monitoring programme. We provide three general recommendations for a strategic monitoring program:

- Continue to support ongoing Australian time series data collection. Australia is clearly depauparate in many long-term baseline datasets, but the past is littered with many discontinued time series that would be very valuable now;

- Implement sampling programmes of additional key biological groups that will form the basis of long-term (>10 year) monitoring. Key systems and groups to monitor in terms of attribution or detection of climate change are highlighted in Table 9-1. These include cold-water corals, demersal fish, plankton, rocky reefs and kelps, soft-bottom benthic and tropical corals. Of these, there are already significant programmes monitoring many of these groups except deep-sea corals, plankton, rocky reefs and kelps, and soft-bottom benthic fauna are critical gaps;

Table 9-1. Biological groups recommended as key indicators of climate change impacts in Australia

Group	Justification
Deep-sea corals	Sensitive to climate change; high levels of endemism of associated species; very little known
Plankton	Important as primary and secondary producers; important trophically; large changes in distribution, abundance and phenology expected
Rocky reefs and kelp	Cheap to monitor; easily accessible; changes in distribution and abundances expected
Soft-sediment fauna	Important trophically; high diversity; likely to be sensitive to changes in primary productivity

- Monitoring and modelling should be developed in partnership. Models require the monitoring of changes in species or habitats for their intialisation, validation and refinement. However, models can inform monitoring programmes about the key species, regions and processes that need to be monitored.

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