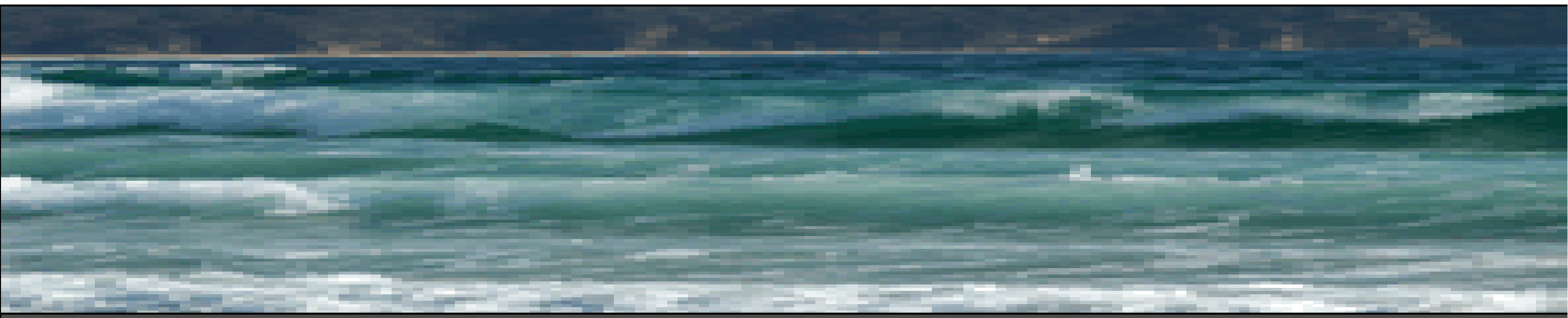
Australian Government
Department of the Environment and Heritage
Australian Greenhouse Office

Impacts of Climate Change on Australian Marine Life

Part B: Technical Report



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

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Part B. Technical Report
Part C. Literature Review

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1. INTRODUCTION

1.1 Australia's unique marine context

The potential impact of climate change on marine life and ecosystems in Australia is considerably less well understood than for the terrestrial biosphere, or indeed other marine systems globally. However, Australia has many unique and important marine ecosystems and species that are likely to be sensitive to climate change (see Box 1). The endemism of marine organisms (species found nowhere else) is very high along Australia's southern coastline. As the temperature envelopes (area of suitable environment) of these continental shelf and slope organisms shift southward in response to ocean heating, organisms will be unable to follow these southward moving envelopes due to a lack of shelf habitat between southern Australia and Antarctica. Marine biodiversity is also high in northern Australia, as a continuation of the Indo-Pacific biodiversity hotspot, but much of this fauna is threatened by over-harvesting and unregulated development to the north, including illegal, unregulated, and unreported fishing. Australia thus potentially provides a critical sanctuary for many endangered organisms in the Indo-Pacific region.

Box 1: Australia's Unique Marine Biodiversity

It is estimated that about 2/3 of the world's biodiversity is marine, though only about 1/6 of the world's 1.5 million described species are marine (it has been roughly estimated that 20 million species might inhabit Earth). Invertebrates make up about 95% of marine species diversity, and of 32 invertebrate phyla 31 are found in oceans, 15 in freshwater, and 10 in terrestrial habitats.

Australia's marine realm harbours an exceptionally high biodiversity, despite generally low levels of productivity. There are two main reasons for this high marine biodiversity. Firstly, northern Australia is situated just south of, and connected to, some of the world's 'hottest' hot-spots of tropical marine biodiversity. Secondly, southern Australia's temperate marine habitats are extremely isolated biogeographically from the other temperate marine habitats around the world thus allowing unique species to evolve there.

One way to illustrate the uniqueness Australia's marine biodiversity is by examining rates of *endemism*—the proportion of species found nowhere else. The following marine endemism rates have been indicated for southern Australia (from Richer de Forges et al 2000, Phillips 2001, Poore 2001, Williams et al 2006):

Fish	85%
Echinoderms	90%
Molluscs	95%
Macro- and mega-invertebrates on seamounts	29-34%
Temperate seaweeds	62%

These estimates clearly underscore Australia's global responsibility for the conservation of marine biodiversity.

Australia's coastal, shelf, and open ocean systems are generally low in productivity (oligotrophic) due to low nutrient runoff from the land, minimal upwelling of nutrient–rich currents, and the influence of northern tropical waters. The impact of changing productivity on such an oligotrophic system is unknown, although they might not be as resilient to stress and disturbance (e.g. climate change) as more productive systems that commonly experience considerable interannual variability. Importantly, changes in the terrestrial climate might impact Australia's marine ecosystems to a greater degree than with other countries, so we cannot easily generalise from observations elsewhere in the world. Much of Australia is desert and it is possible that dust input is an important regulator of coastal primary production. Thus, climate-induced changes in wind or rainfall might have disproportionately large consequences for the Australian coastal and ocean systems.

1.2 Vulnerability of Australia's marine realm to climate change

The Allen Report (2005) defines vulnerability as a function of exposure to climate factors, sensitivity to change, and capacity to adapt to that change (**Figure 1-1)**. Systems that are highly exposed, sensitive, and less able to adapt are extremely vulnerable. Strategies for adaptation to climate change impacts on marine life must begin with the identification of ecosystems or populations that are vulnerable to change and the identification of threshold or trigger values that may drive systems into irreversible change. Such strategies must also include an examination of the potential for increasing the coping capacities—the resilience—of these ecosystems and populations so that their vulnerability to climate change can be reduced. This is possible because non-climate related stressors (not depicted in **Figure 1-1**) are known to decrease the resilience (increase the vulnerability) of marine life and ecosystems to climate change impacts, and these stressors can be managed far more readily than global climate changes by altering policy and management practices on national and regional scales.

The goal of the present review is to provide a theoretical and practical framework for prioritisation of policy and management strategies by creating an approach that will highlight the Australian marine ecosystems or regions that are facing the most significant consequences of climate change impacts ecologically, socially, and economically. It is important to remember that the oceans are likely to respond more slowly to climate change than the atmosphere. Although this means that climate impacts on biology may be slower to manifest, it also implies that the ecological response to any mitigation strategies that can be implemented will be slower. For example, it has been calculated that ocean acidification is essentially irreversible during our lifetimes and it will take tens of thousands of years for ocean chemistry to return to a condition similar to that occurring at pre-industrial times (about 200 years ago) (Raven et al. 2005).

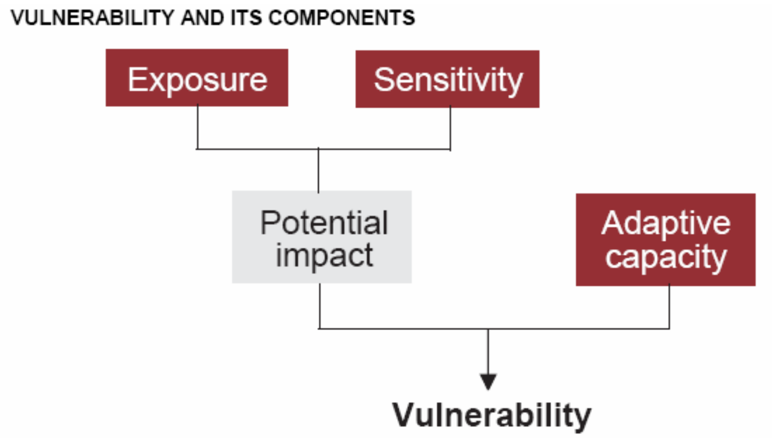

Figure 1-1. Vulnerability has been defined as the intersection of the potential impact on natural or human systems (determined by exposure and sensitivity) and their adaptive capacity (taken from Allen Report, 2005).

2. DRIVERS OF CLIMATE CHANGE IN THE OCEAN

Richard J. Matear, CSIRO Marine and Atmospheric Research

Australia's marine realm is diverse, ranging from coastal estuaries to the open ocean, with many specialised environments. Given this diversity and the limited ability at present to project future local impacts of global change, we focus on the larger-scale general trends projected by climate models. This chapter is not an extensive review of all the environmental changes projected with global warming; rather, it first provides a synopsis of the robust features to emerge from climate simulations of global warming, and then gives two examples of changes in the environment that we expect to most impact marine biodiversity.

A range of climate models have been used to investigate the response of the physical ocean-atmosphere system to increased greenhouse gases and aerosols (Cubasch et al. 2001). In general, the climate model simulations of global warming predict oceanic temperature increases, dramatic changes in oceanic stratification, circulation and convective overturning, and changes in cloud cover and sea ice, and thus light supply to the surface ocean. It is highly likely that such changes will cause significant alterations in marine ecosystems (Bopp et al. 2001, Boyd and Doney 2002, Sarmiento *et al.* 2004). Here we utilise the most recent climate change projection from the CSIRO Mk3.5 climate model (hereafter called the CSIRO climate model) (**Box 1**). Although there are subtle differences between the CSIRO climate model and other international models, many of the general trends in the output fields are similar and we focus on these trends rather than the absolute magnitude of predicted changes.

The present report is focused on the effect of several environmental variables that are important to Australian marine life (**Table 2-1**). These environmental variables affect the growth, reproduction, distribution and overall success of marine organisms (Hughes et al. 2000). [These environmental variables are also used in Chapter 3 of this report (Part B) as indicators for the climate change dimension to rate vulnerability for seven large marine domains around Australia]. The present chapter serves to illustrate the impact of climate change on the Australian marine environment by presenting projections for probably the two most important aspects of global warming for marine life: sea surface temperature (SST) warming and ocean acidification.

Table 2-1: Physical climate change indicators used to quantify the impact of global warming on Australian marine life.

Oceanographic	Atmospheric
Sea Surface Temperature (°C)	Incident solar radiation (W m^{-2})
Temperature (at 500 m depth)	Wind speed (m s^{-1})
Sea Surface Salinity (psu)	Wind direction
pH	Freshwater flux into ocean (mm d^{-1})
Mixed Layer Depth (m)	
Surface Current (cm s^{-1})	

Box 1. The CSIRO Mk 3 Climate System Model

The CSIRO Mk 3 Climate System Model is a state-of-the-art climate model that represents all the major components of the earth's climate system – atmosphere, land surface, sea-ice, and oceans. The version Mk 3.5 is the most recent update of the model. CSIRO Mk 3 model simulations are an important contribution to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report. For climate projections in this study we use the IPCC SRES A2 greenhouse gas emission scenario, which projects atmospheric CO_2 levels of 536 ppm by 2050.

A detailed description of the model is given in Gordon et al. (2002), and summarised here. The CSIRO Mk 3 atmospheric module has a spectral T63 horizontal grid (≈1.875° latitude by 1.875° longitude) with 18 vertical levels (hybrid sigma-pressure vertical coordinate). The atmospheric model includes comprehensive parameterisations of cloud microphysics and convection, which are linked via the detrainment of liquid and frozen water at the cloud top. Atmospheric moisture advection (vapour, liquid and frozen) is performed by the semi-Lagrangian method. This module includes the direct radiative forcing of sulfate on atmospheric albedo. The land-surface scheme uses six layers of moisture and temperature with a vegetation canopy. The scheme uses nine soil and twelve vegetation types, and includes a three-layer snow model.

The sea-ice module incorporates a dynamic thermodynamic polar ice model that includes a variable fraction of leads. The ocean model is based upon the Modular Ocean Model version 2.2 (MOM2.2) of the Geophysical Fluid Dynamics Laboratory model. The oceanic component has horizontal resolution of ≈ 0.9375° latitude by 1.875° longitude. For every atmospheric grid point there are two ocean points in the meridional direction, which allows for the atmospheric model and ocean model subcomponents to have matching land-sea masks. There are 31 levels in the vertical, with the spacing of the levels gradually increasing with depth, from 10 m at the surface to 400 m at depth. The ocean model includes a parameterisation of mixing of tracers (Griffies et al. 1998), and improved vertical mixing in the tropical Pacific.

Sea surface temperature (SST) warming and large-scale currents

The CSIRO climate model projects waters around Australia to warm by 1-2°C by the 2030s and 2-3°C by the 2070s, with the greatest warming off south-east Australia in the Tasman Sea. (**Figure 2-1**). The projected warming is a consequence of a strengthening of the East Australian Current (EAC) and increased southward flow as far south as Tasmania. This feature is present in all IPCC climate model simulations, with only the magnitude of the change differing between models. The 60-year record of temperature at Maria Island, off the east coast of Tasmania, already shows intense warming at the surface and at 50 m depth of 0.15°C per decade. The largest increases (0.3°C per decade) were over the transition months of May and November, when the EAC extends into and retreats from Tasmanian waters (Ridgway & Godfrey 1997).

The projected Tasman Sea warming is also driven by a southward migration of the high westerly wind belt south of Australia in the future (Cai et al. 2005, Cai 2006). The westerly wind belt in the Southern Hemisphere has already shifted southward over the last several decades (Thompson & Solomon 2002). In the CSIRO projections, there is no obvious strengthening of the Leeuwin Current on the west coast of Australia, although there is more westward transport along the southern coast through the Great Australian Bight.
This has implications for the distribution of marine species and connectivity of marine populations.

Most of Australia's coastal systems are downwelling regions, or they have stratified water columns, due to the prevailing winds and density structure of the upper ocean. This means that most Australian waters are nutrient poor (oligotrophic) rather than nutrient-rich upwelling regions, especially in the tropics and sub-tropics. Here, the dominant mechanism of nutrient supply to the upper ocean is convective mixing in winter due to cooling of the surface water. The projected surface ocean warming would result in a more stable ocean, with less mixing and therefore a reduced supply of nutrients to the upper ocean, resulting in declining primary (phytoplankton) and secondary (zooplankton) productivity.

Ocean acidification

The world's oceans absorb CO_2 naturally from the atmosphere, acting as a buffer for increasing atmospheric CO_2. However, rising atmospheric CO_2 concentrations via fossil fuel emissions are leading to an increase in oceanic CO_2 , as the ocean attempts to re-equilibrate with the perturbed atmosphere (McNeil et al. 2003). In fact, it has been estimated that the global oceans have soaked up half of the anthropogenic induced CO_2 from the atmosphere, which means the current state of global warming has been dampened somewhat by this phenomenon. Oceans do have a limit to this buffering capacity, so that the increased CO_2 in the upper ocean has changed the chemical speciation of the oceanic carbon system, making the world's oceans more acidic (see Box 2). What is of most concern is the rapidity of this change.

Box 2. The fate of CO_2 in ocean waters

As CO_2 enters the ocean it undergoes the following reactions:

$$CO_2 + H_2O \Leftrightarrow H_2CO_3 \Leftrightarrow HCO_3^- + H^+ \Leftrightarrow CO_3^{2-} + 2H^+$$

Increasing CO_2 concentrations in the surface ocean via anthropogenic CO_2 uptake will have two effects. First, it will decrease the surface ocean carbonate ion concentration (CO_3^{2-}) and decrease the calcium carbonate saturation state. Second, when CO_2 dissolves in water, it forms a weak acid (H_2CO_3) that dissociates into bicarbonate-generating hydrogen ions (H^+), making the ocean more acidic (pH decreases). Thus, the equation moves from both the left and right side to the center (HCO_3^- + H^+) when CO_2 rises.

Two important parameters of the oceanic carbon system are the pH (ie. level of acidity or alkalinity) and the calcium carbonate ($CaCO_3$) saturation state of seawater. The pH of seawater is defined by the amount of H^+ ions available: $pH = -\log_{10}\left[H^+\right]$. The calcium carbonate saturation state of seawater expresses the stability of the two different forms of calcium carbonate (calcite and aragonite) in seawater.

Using an ocean-only model forced with atmospheric CO_2 projections (IS92a), a 40% reduction in aragonite saturation is predicted by 2100 (Kleypas et al. 1999). Laboratory experiments have shown some species of corals and calcifying plankton are highly sensitive to changes in calcium carbonate saturation (Gattuso et al. 1998, Langdon et al. 2000, Orr et al. 2005). This finding has led to the realisation that there will be large decreases in future calcification rates if atmospheric CO_2 is elevated (Raven et al. 2005). Further, a pH drop of 0.4 units is predicted by the year 2100 and a further decline of 0.7 by the year 2300 Caldeira & Wickett (2003). The oceanic absorption of anthropogenic CO_2 over the next several centuries may result in a pH decrease greater than those inferred from the geological record over the past 300 million years, with the possible exception of those resulting from rare, extreme events. Critically, this rapid rate of pH decrease in the future may be faster than the rate at which species can adapt.

Future acidification may adversely impact marine biota (Raven et al. 2005), but our understanding of the biological response is limited. Experiments to determine the likely response of marine organisms to pH changes have explored large changes in pH (> 1) under laboratory conditions for only a few organisms (Kikkawa et al. 2003, Pedersen & Hansen 2003a, 2003b, Barry et al. 2004, Portner et al. 2004, Engel et al. 2005). Little is known on what the gradual long-term effects of lowering pH will be on any marine organism. Changes in surface pH and in aragonite saturation state reflect changes in the speciation of carbon within the ocean and are a function of temperature, salinity, alkalinity and dissolved inorganic carbon concentrations. Future pH in the ocean will be determined primarily by levels of atmospheric CO_2 rather than the degree of warming (McNeil & Matear 2006). For the Australian region, the pH and aragonite saturation state for the baseline 1990s along with the projected changes by the 2070s are shown in **Figure 2-1**. These parameters decline significantly, with the greatest change in waters off north-east Australia.

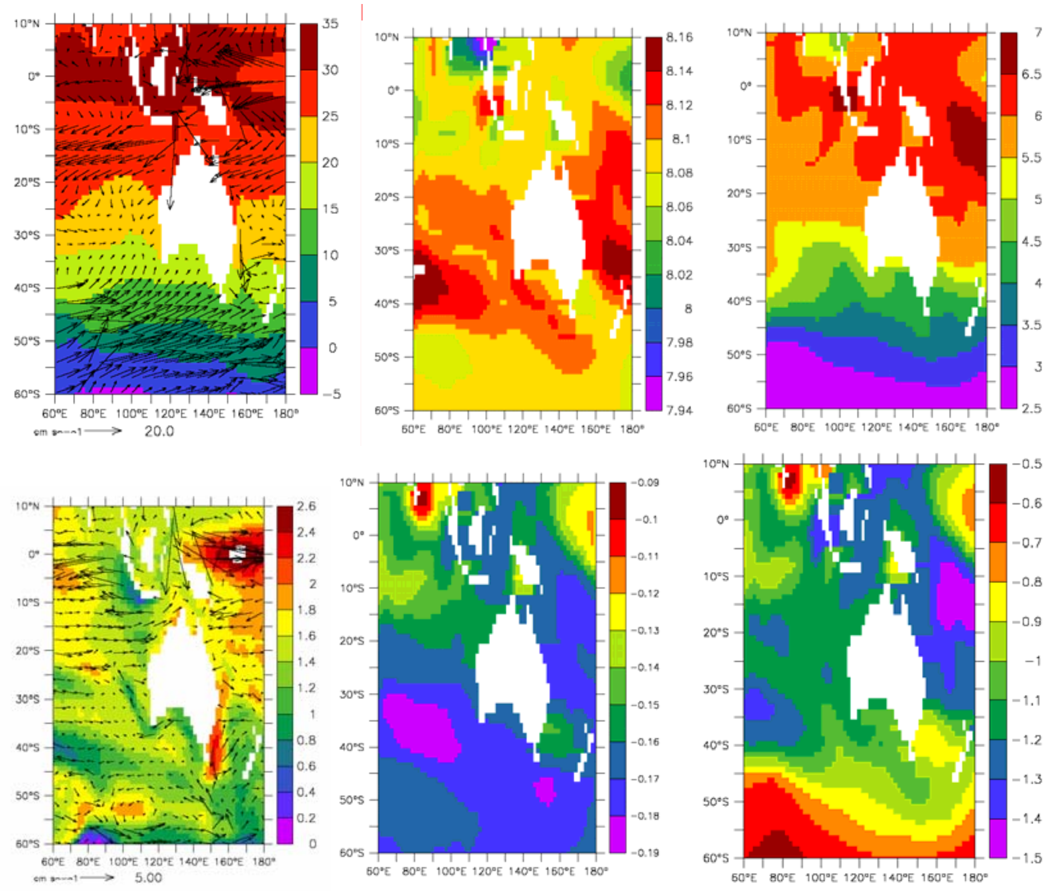

Figure 2-1. Projections of oceanographic change. **Left**: Average Sea Surface Temperature (°C) for the 1990s (upper) and the change in SST between 2070s and 1990s (lower). **Middle**. Averaged pH for 1990s (upper) and the change in pH between 2070s and 1990s (lower). **Right** Averaged aragonite saturation state for the 1990s (upper) and the change between 2070s and 1990s (lower)

3. RATING THE VULNERABILITY OF AUSTRALIAN MARINE LIFE TO CLIMATE CHANGE

Alistair J. Hobday, Elvira S Poloczanska, Thomas A. Okey, Anthony J. Richardson and Thomas J. Kunz, CSIRO Marine and Atmospheric Research

The Allen Report (2005) states that "Vulnerability [of a natural or human system] is a function of exposure to climate factors, sensitivity to change and capacity to adapt to that change. Systems that are highly exposed, sensitive and less able to adapt are vulnerable". Vulnerability is defined here as the potential for marine life, habitats, or ecosystems to be altered or lost as the result of climate change.

We developed a scheme to evaluate the broad-scale vulnerability of biodiversity to risks posed by climate change and to compare vulnerability among large marine domains in Australia. Adaptative management strategies to mitigate climate change impacts will require the identification of regions and biota most vulnerable to climate change and also regions where change is likely to carry the most significant consequences. Precise effects of climate change are difficult to predict due to the complexity of ecosystems and the subtlety of particular effects. Our approach represents the first attempt on a national scale to estimate the vulnerability of marine biodiversity to climate change. Our generic approach can be applied and adapted easily to assessments of marine life vulnerability in other regions of the world, and it should aid managers and policy makers to prioritise research, data collection, and policymaking.

Vulnerability is the intersection of three elements: exposure (to climate change effects), sensitivity, and adaptive capacity (Allen Report 2005, **Figure 1-1)**. With respect to marine biodiversity:

- *Exposure* relates to the influences or stimuli that impact on a system. Here, exposure is a measure of the predicted changes in the climate of each domain between 1990s and 2070s.
- *Sensitivity* reflects the responsiveness of a system to climatic influences, and the degree to which changes in climate might affect that system *in its current form*. Sensitive systems are highly responsive to climate and can be significantly affected by small climate changes.
- *Adaptive capacity* reflects the ability of a system to change in a way that makes it better equipped to deal with external influences. While we cannot measure this directly, we can measure other stressors on biodiversity that will reduce a system's inherent capacity to adapt to a rapidly changing climate.

We have rated overall climate change vulnerability within each of seven large marine domains that surround continental Australia. Large marine domains were the scale of analysis chosen for this exercise because data limitations prevented the finer IMCRA (Interim Marine and Coastal Regionalisation for Australia) bioregionalisation from being used (60 small regions around Australia), and because the IMCRA boregionalisation does not extend to the shelf break.

3.1 Approach to developing a vulnerability index

We based our vulnerability index rating system roughly on an approach developed for assessing livelihoods in rural areas (Carney 1998, Nelson et al. 2005) which ranked the vulnerability of systems to a given set of externally imposed changes along multiple dimensions of vulnerability. This transparent approach to estimating overall vulnerability is useful qualitatively because it enables each reader to apply their own conceptual weightings to the different dimensions of vulnerability. Vulnerability can also be thought of as a function of the different assets and stressors of a system so the ability to respond to change is a dynamic interaction of these. We have identified indices that describe the present state of biodiversity vulnerability in each domain and have grouped these into four dimensions that will also help inform adaptive management of ecosystems (**Table 3-1**), and a fifth dimension representing predicted climate and oceanographic changes until 2070s.

Using this framework, rating the vulnerability of Australia's marine biodiversity to climate change involved six steps:

1. Explore availability of data for vulnerability indicators;
2. Select reasonable indicators of current state of biodiversity in each region;
3. Group into appropriate dimensions of vulnerability;
4. Score each indicator on a standardised quantitative scale;
5. Evaluate the redundancy and performance of each indicator;
6. Calculate overall vulnerability indices.

The five dimensions of vulnerability (**Table 3-1**) were selected to represent the different aspects of stress that impact biodiversity in marine regions. Climate change will not act alone, but is a cumulative stressor, such that regions with existing pressures may be more vulnerable. Although weighting of the dimensions is possible, and might be required if one dimension contributes more strongly to overall vulnerability than another, there is currently insufficient information for such a weighting system. Future versions of the vulnerability rating system may include a weighting aspect provided that knowledge of impacts increases sufficiently.

Data for each of these indicators are used to produce a value scaled between 1 (low) and 5 (high) to indicate the degree of vulnerability. This allowed indicators with very different units or ranges to be compared and averaged for each dimension of vulnerability (see Nelson et al. 2004, Hobday et al. 2004). Indicators shown here were chosen according to data availability, redundancy, and performance. Redundancy was encountered when two indicators measured the same biodiversity-vulnerability aspect thus exaggerating risk, or when one indicator was conditional on another. Performance is related to the quality of data, the geographical extent of data, and its ability to measure change or be a proxy of change that would increase vulnerability. Indicators such as overexploited fisheries and concentration of heavy metal compounds are familiar to many marine scientists and policy makers as having detrimental effects on marine life. The overall score for a dimension was the mean of the indicator scores. The rationale for each of the indicators is provided in **Appendix 1.**

Table 3-1: Five dimensions of vulnerability of Australia's marine biodiversity to climate change and the indicators chosen to represent those five dimensions. See Appendix 2 for details. The relationships between each indicator and vulnerability of marine life to climate change were always positive, except for total area, where a negative relationship is indicated. The vulnerability component refers to the element of vulnerability represented by each indicator as defined in the Allen report (2005): S = sensitivity, AC = adaptive capacity, E = exposure.

Dimension	*Indicator*	*Vulnerability Component*
Biological	B1: Number of threatened species	S
	B2: Number of endemic demersal slope fish	S
	B3: Percent introduced species per port	S
	B4: Community uniqueness	S
Regional characteristics	R1: Total area	S
	R2: Proportion foundation species area (depth< 50 m)	S
	R3: Poleward boundedness	S
Climate change	C1:% change in sea surface temperature (SST)	E
	C2: % change in temperature at 500 m depth	E
	C3: % change in mixed layer depth	E
	C4: % change in incident solar radiation	E
	C5: % change in surface currents	E
	C6: % change in surface winds	E
Fishing stress	F1: Fisheries gear impact – habitat	AC
	F2: Fisheries gear impact – bycatch	AC
	F3: Overexploited fisheries	AC
	F4: Number of fisheries hours	AC
	F5: Number of AFMA fisheries	AC
	F6: Recreational fisheries use	AC
Other anthropogenic	A1: Coastal development	AC
	A2: Organic compounds	AC
	A3: Chemical compounds	AC
	A4: Heavy metals	AC
	A5: Chemical dump sites and tracks	AC
	A6: Ship visits	AC
	A7: Oil and gas wells	AC
	A8: Seismic surveys	AC

3.2 Climate change vulnerability in Australia's Large Marine Domains

The ranks for each of the 29 indicators are shown in **Appendix 2**. The relative vulnerability for each dimension varied between domains, with some domains being highly vulnerable for one dimension but low for another.

Overall vulnerability of marine biodiversity in Australia

The vulnerability index developed here shows that a medium to high vulnerability is indicated for all of the domains and that the most vulnerable domains are the Eastern Central and South Eastern domains (**Figure 3-1**). The least vulnerable marine domain, with respect to threats to biodiversity for the dimensions considered is the South Western Domain.

The easiest way to compare the vulnerability of a domain in terms of each dimension of vulnerability is to use a kite diagram. The kite diagrams show that vulnerability varies between regions and dimensions (**Figure 3-2**) and allows ease of comparison. The kite diagram shows relative risk along each arm of the kite, with low risk towards the centre and high risk towards the outside. Each domain is connected around the arms of the kite. For example, the relative vulnerability along the fishing stress dimension is highest for the South Eastern domain and lowest for the North Western, while for the climate change dimension the Eastern Central domain rates highest. The contribution of each of the dimensions to this overall vulnerability can be understood by considering each separately (**Figure 3-3**), and the analyses of the separate dimensions are where planners and policymakers should begin looking for strategies to decrease the vulnerability of Australia's marine life to climate changes.

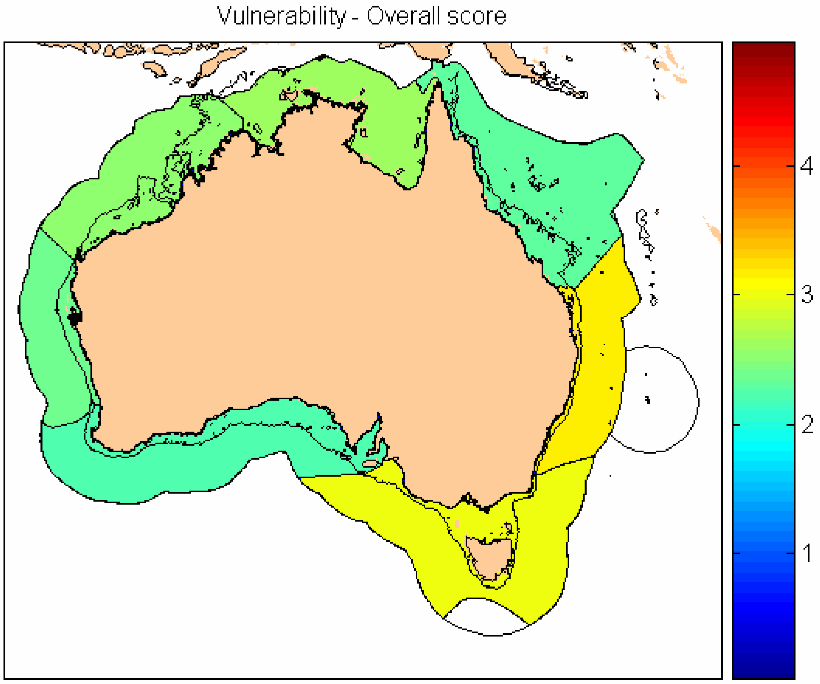

Figure 3-1. Overall vulnerability of Australia's large marine domains as expressed by the average score for each of the five dimensions of vulnerability. Beginning from Tasmania, and moving clockwise, the Australian coastal domains are South Eastern Domain, South Western Domain, Western Central Domain, North Western Domain, Northern Domain, North Eastern Domain and Eastern Central Domain.

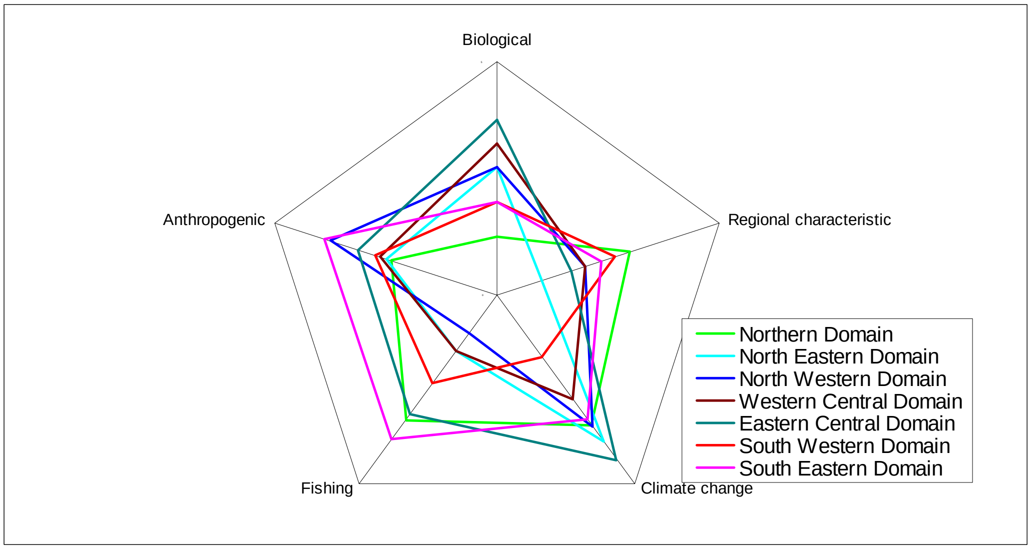

Figure 3-2. Kite diagram allowing comparison of vulnerability for each of the dimensions for the seven large marine domains around Australia. Lines furthest from the centre on each axis indicate highest risk for that component.

Dimension 1: Biological

The Eastern Central Domain is the most vulnerable domain with regard to the Biological Dimension (**Figure 3-3A)**. The highest scoring indicators for this domain were the total number of threatened, endangered and protected (TEP) species and the uniqueness of those threatened species. The Northern Domain was the least vulnerable, with fewest introduced species, fewest threatened species, fewest unique TEP species, and low numbers of endemic demersal slope fish.

Dimension 2: Regional characteristics

The Northern Domain was the most vulnerable in this dimension, due to high scores for possessing the greatest amount of shallow area that is suitable for foundation species (**Figure 3-3B)**. The least vulnerable domains based on the regional characteristics were the Eastern Central and the North Eastern domains. The low ranking indicators for these domains were the limited foundational area and having domains to the south to allow movement of biodiversity with ocean warming.

Dimension 3: Climate change

The Eastern Central Domain was the most vulnerable with respect to climate change indicators (**Figure 3-3C**). The amount of change expected in the climate indicators in this region was greatest for three of the seven indicators, including changes in sea surface temperature, sub-surface temperature, and surface winds. The South East Domain was less vulnerable, even though it includes a large part of the Tasman Sea, where warming is predicted to be greatest in the southern hemisphere (Cai et al. 2005). However, this domain also encompasses the eastern Great Australian Bight, where cooling due to increased winds and upwelling is predicted. The latter partially cancels out warming in the remainder of the domain, resulting in an intermediate climate impact signal.

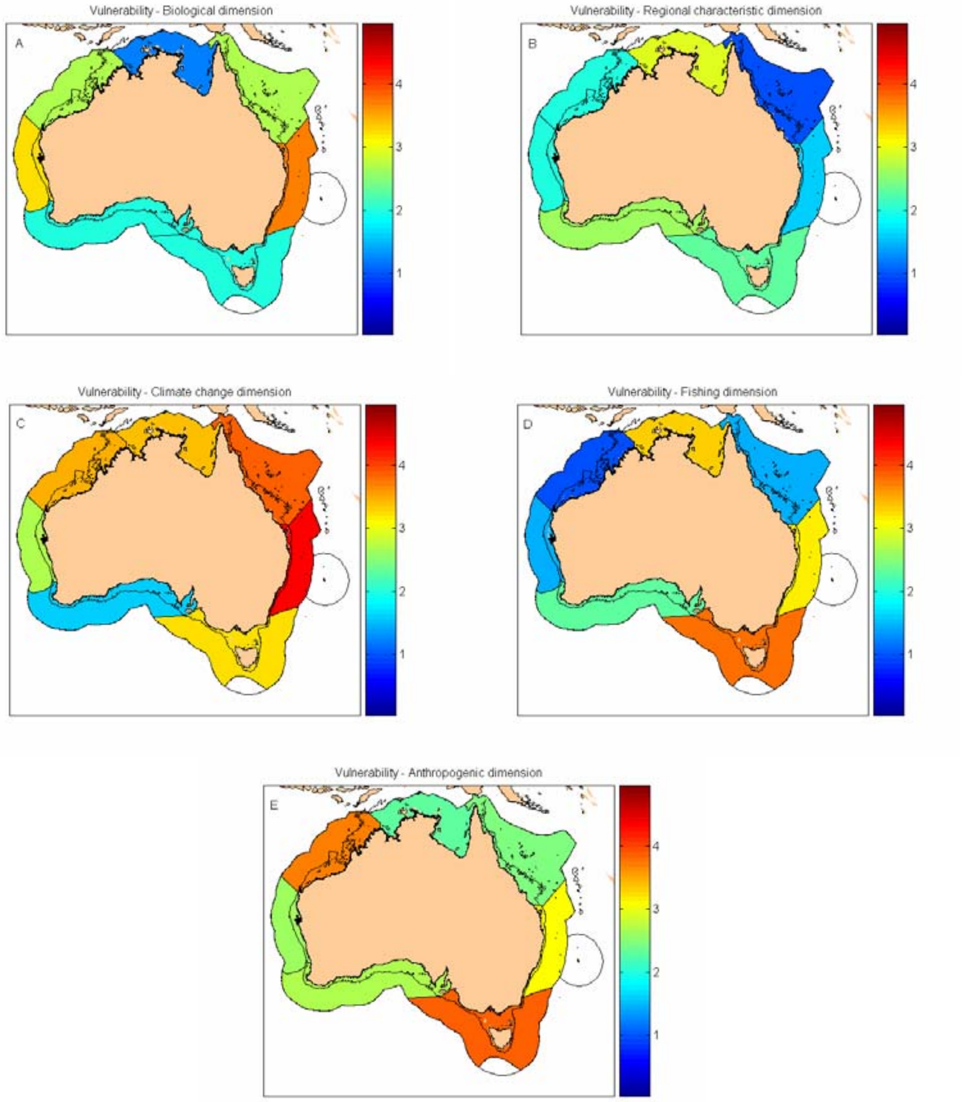

Figure 3-3. Vulnerability maps for each of the five dimensions (A-E) for the seven large marine domains in Australia. Note that the vulnerability scores vary between dimensions. Beginning from Tasmania, and moving clockwise, the Australian coastal domains are South Eastern Domain, South Western Domain, Western Central Domain, North Western Domain, Northern Domain, North Eastern Domain and Eastern Central Domain.

Dimension 4: Fishing

The South East Domain was most vulnerable with respect to fishing stress while the lowest such stress was found for the North West Domain (**Figure 3-3D)**. This seems plausible, as these regions are closest to and furthest from population centres, respectively. However, the fishing stress dimension did not include an indicator for illegal, unregulated, and unreported (IUU) fishing, so our estimate of vulnerability by fishing in the North West Domain and the Northern Domain is under-estimated. Thus, with regard to fishing, this domain scored the lowest vulnerability, when in fact it is likely to be quite high. Quantification of IUU fishing is expected to improve in the near future, so such indicators can be included in subsequent analyses.

Dimension 5: Other Anthropogenic

The South East and North West domains had the greatest vulnerability for the anthropogenic dimension (**Figure 3-3E)**. The North West Domain scored highly for five indicators such as oil and gas wells, shipping, and pollution risk from heavy metals, organic and chemical compounds, due to oil and gas exploration in the area. The South East Domain scored highly for indicators such as heavy metals and chemical dumps, and was at medium levels for the remaining indicators.

3.3 Caveats with this approach

The vulnerability index highlights domains in which marine life is likely most vulnerable to climate change. However, several caveats that relate to the availability, quality, or consistency of data must be considered when interpreting these results. First, the domains are large, and hence may contain signals of opposite direction which may cancel out (see example in *Dimension 3: Climate Change* section). Currently, a lack of data for some indicators does not permit use of smaller domains. Second, critical indicators such as illegal fishing activity for the Fishing Stress Dimension, also could not be included because of a lack of data. Finally, data quality and consistency may be an issue as highlighted by the Number of Threatened Species indicator (see above). Generally, because several indicators were averaged per dimension, the technique should be robust to imprecise or crude information for any one indicator. Our vulnerability index should be considered as a useful tool, but at this stage in development we caution against uncritical application.

Main Findings: Vulnerability of Australia's large marine domains

- **This index represents the first national ranking of Australia's marine domains to the impacts of climate change**
- **Vulnerability was assessed using 29 indicators in five dimensions, including biological, regional, climate change, fishing stress and other anthropogenic stressors.**
- **Impacts vary by domain; some impacts are high in one area, and not in another.**
- **Overall, the Eastern Central Domain and the South-east Domain are the most vulnerable to the impacts of climate change**

4. LONG-TERM AUSTRALIAN MARINE DATASETS FOR IDENTIFYING CLIMATE IMPACTS

Anthony J. Richardson, Alistair J. Hobday, Elvira S Poloczanska, Thomas A. Okey and Thomas J. Kunz, CSIRO Marine and Atmospheric Research

In this review we have detailed the expected dramatic and observable consequences of climate change for marine groups, some of which are already being observed in Australian waters such as bleaching of tropical corals. At present, it is impossible to determine if climate change is impacting on many less charismatic marine groups and habitats in Australia, despite compelling evidence from elsewhere in the world.

Key to documenting and understanding the response of species to climate change are long-term baselines (Southward 1995). Australian marine scientists have long claimed that the lack of observable climate signals in biological data is a consequence of the paucity of time series in the region. This claim is not unique to Australia. Despite an exponential increase in the initiation of long-term monitoring programmes in the world's oceans since World War II, 40% of these time-series were stopped during the 1980s because monitoring was seen as poor science by administrators (Duarte et al. 1992). This negative perception only altered during the late 1990s when the consequences of climate change were seen both scientifically and politically as being important, and this has markedly improved the fortunes of many programmes (Hays et al. 2005).

Despite the turn-round in global trends in long-term research, there is still considerable evidence that Australia has under-invested in marine time series. **Table 4-1** provides a summary of Australian datasets that do exist. Our criteria for inclusion in this list was that there should be at least 4 years of data and it must have been collected in a consistent manner in the same region. We initially sought only time series more than 10 years in length but very few time series qualified, and so we relaxed the criteria. Many of the marine groups reviewed in Part C of this report have no time series, and many time series that did exist have been terminated.

Gaps in our present monitoring system are numerous, but the case of zooplankton sampling in Australia highlights the situation. Zooplankton are the most abundant multicellular organisms on the planet, are the major source of food of many marine organisms, and are considered sentinels of climate change (Hays et al. 2005). However, the longest zooplankton time series in Australia is only five years and was discontinued more than 60 years ago. The longest extant time series is two years and consists of a single cross-shelf transect for all of Australia. Given the diversity of marine habitats in Australia and the economic and social importance of fishing, this does not compare favourably with the rest of the world; the UK has at least four plankton datasets that span more than 40 years. Globally there are zooplankton time series spanning more than 15 years in no fewer than 30 countries, including relatively poor and developing nations, such as Bulgaria, Chile, Estonia, Greece, Kazakhstan, Latvia, Faroe Islands, Namibia, Peru, Turkey and the Ukraine[1]. Australia is clearly depauparate in long-term baseline zooplankton datasets urgently required to assess climate change impacts. This situation of a paucity of sampling is equally applicable to other marine groups including soft bottom fauna, rocky shore fauna, mangroves and phytoplankton.

Many of the datasets that do exist are housed by CSIRO Marine and Atmospheric Research. CSIRO provides an easily-accessible, searchable metadata repository called MarLIN (Marine Laboratories Information Network; http://www.marine.csiro.au/marlin/). Data that are found via MarLIN and are open access can be downloaded via DataTrawler (http://www.marine.csiro.au/warehouse/jsp/loginpage.jsp). As of 2006, MarLIN contains descriptions of 2,400 datasets. Despite this seemingly vast resource, on perusing the database it quickly becomes apparent that there are very few real time series where consistent, repeated measurements were collected in the same area over multiple years.

Table 4-1 should prove valuable for Australian long-term research in four key ways. First, it lists datasets that can form the basis for future research aimed at identifying climate signals. Second, it can inform researchers and decision makers about datasets that could be re-established by initiating sampling programmes that would enable comparisons with historical data. Third, it highlights marine groups and geographical areas where no adequate time series are available. Last, it includes information on the most valuable environmental time series available, which are needed to identify relationships between biota and physical forcing.

Extant time series increase in value each year and need to be continued and supplemented by additional time series for under-sampled biota. Long-term research has been given a recent boost in Australia with the advent of the Integrated Marine Observing System (IMOS). Its aim is to understand and ensure the long-term health and productivity of Australia's marine environment, and to predict climate variability and change by accurately and rapidly detecting changes in the marine environment. A substantial part of this project is to collect data and make them accessible; this represents a real opportunity for the Australian marine science community to initiate long-term programmes. Unfortunately, many biological time series require taxonomic expertise and sample processing and are seen as relatively expensive compared with more-automatic methods of collection focusing on physical variables. Although new molecular approaches are emerging to aid in the identification of species during monitoring, it is critical to maintain a pool of qualified taxonomists to guide and interpret these new methods and data and to continue describing new species. Unfortunately, Australia now has an extreme shortage of trained marine taxonomists given Australia's tremendous biodiversity, both described and undescribed. This pool of taxonomists is aging and is not being replaced. Australia has lagged far behind its international counterparts in understanding climate change impacts on marine ecosystems. Continuing to neglect the collection of long-term biological baselines and the deficit in taxonomists is strategically reckless, especially knowing that climate changes will likely impact Australia's marine ecosystems and marine-related industries severely.

Main Findings: Long-term datasets

- **Australia currently has a poor network of marine time series for assessing climate change impacts**
- **Although most marine groups do not have adequate baselines, the scarcest data are for the non-commercial and non-charismatic groups such as phytoplankton, zooplankton, soft-bottom fauna, mangroves and rocky shores (e.g. intertidal)**

Table 4-1. Summary of important time series data available in Australia, including variables measured, the name of the dataset, where and when it was collected, and general information and accessibility of the data. CMAR = CSIRO Marine and Atmospheric Research. Highlighted time series are longer than 10 years

Variables	Dataset	Where	When	Information and accessibility
Biological				
Mangroves	None found			
Seagrasses	Sea Grass Watch	Australia (16 regions) and 12 other countries	Quarterly Since 2000	Data freely available from http://www.seagrasswatch.org/home.html
Kelp forests	Tasmanian Giant Kelp Time Series	8 sites in Tasmania	Irregular from 1890-1999	Available as aerial maps from Tasmanian Department of Primary Industries and Water at http://www.dpiw.tas.gov.au/inter.nsf/Publications/HMUY-5TT2P6?open
Coral reefs	Reef Monitoring	Great Barrier Reef (48 reefs)	Annual Since 1995	Data includes algae, fish, crown-of-thorns. Contact the Australian Institute of Marine Science at http://www.aims.gov.au/pages/research/reef-monitoring/projinfo.html
	Heron Island	Great Barrier Reef	Annual Since 1962	Coral census. Contact Terry Hughes (terry.hughes@jcu.edu.au) for more details
		Palm Island and Maggie Island	Annual Since 1998	Adult coral abundance (Marshall & Baird 2000). Contact Andrew Baird (andrew.baird@jcu.edu.au) for more details.
		Lizard Island	1995-1998	Coral recruits and adults. Contact Andrew Baird (andrew.baird@jcu.edu.au) for more details.
		Reefs off Townsville and Lizard Island	Annual 1980 - 2005	Coral communities from photographic transects. Contact Terry Done (t.done@aims.gov.au) for details.
Deep sea corals	None found			
Rocky shore macrofauna	None found			
Soft bottom benthic infauna and epifauna	19 Baseline biological port surveys conducted by CRIMP	Ports around Australia	1996-present	Data freely available via CMAR Data Trawler at http://www.marine.csiro.au/warehouse/jsp/loginpage.jsp
Phytoplankton	Albatross Bay Phytoplankton Data	Albatross Bay, Gulf of Carpentaria	1986-1992	Data available from Tony Rees (tony.rees@csiro.au) at CMAR on request
	CRIMP Survey	Ports around Australia	1996-present	HAB species. Contact CSIRO at http://www.marine.csiro.au/crimp/nimpis/Default.htm
	Port Hacking	Sydney	Monthly Since 1997	Counted only for *Noctiluca scintillans*
Zooplankton	SRFME Zooplankton &	Transect off Perth	2003-present	Contact Tony Koslow (tony.koslow@csiro.au) at CMAR. See also

Variables	**Dataset**	**Where**	**When**	**Information and accessibility**
	Ichthyoplankton			http://www.srfme.org.au/coreres/project_one.htm for more information
	Warreen Plankton Data	Southeast Australia	1938-1942	Crustacea (including krill and copepods), chaetognaths, coelenterates, fish eggs and larvae, molluscs and tunicates. Contact Tony Rees at CSIRO Marine and Atmospheric Research tony.rees@csiro.au (CSIRO)
	Warreen Plankton Data	Southwest Australia	1947-1950	Crustacea (including krill and copepods), chaetognaths, coelenterates, fish eggs and larvae, molluscs and tunicates. Contact Tony Rees at CSIRO Marine and Atmospheric Research on tony.rees@csiro.au
	Port Hacking	Sydney	Monthly Since 1997	Samples collected by 100 µm net and are uncounted. Contact Iain Suthers (i.suthers@unsw.edu.au) at University of NSW for details
	Bass Strait	Eastern, Central and Western Bass Strait	1981-1983	Analysis and digitisation required. Contact Gina.Newton@deh.gov.au at the Australian Greenhouse Office
Pelagic fishes	CAAB database (CSIRO Codes for Australian Aquatic Biota)	Australian region	Various	Some data freely available via CMAR Data Trawler at http://www.marine.csiro.au/warehouse/jsp/loginpage.jsp, otherwise contact Tony Rees (tony.rees@csiro.au) at CMAR
	Catch data Observer data	Australia SE fisheries	Various Since 1900	Data available from Australian fisheries agencies Contact Neil Klaer (neil.klaer@csiro.au) at CMAR
	Northwest Shelf Study	Northwest Shelf	1982-1997	Data freely available via CMAR Data Trawler at http://www.marine.csiro.au/warehouse/jsp/loginpage.jsp
Turtles	Mon Repos Time Series	Beach at Mon Repos, SE Qld	Unknown	Contact Col Limpus (col.limpus@epa.qld.gov.au) at Environmental Protection Agency
Seabirds	Environmental Effects of Prawn Trawling	Far northern section of GBR	1991-1996	CSIRO Cleveland. Contact Roland Pitcher (roland.pitcher@csiro.au)
Cetaceans & Pinnipeds	Torres Strait Dugong Community Census	Torres Strait	1983-1989	Contact Tom Taranto, CSIRO (tom.taranto@csiro.au)
Physical (examples)				
SST, Winds, Cloudiness	ICOADS (International Comprehensive Ocean-Atmosphere Data Set)	Global 1°	Monthly 1960-2005	Ships of Opportunity data available freely at http://icoads.noaa.gov/
SST	AVHRR Pathfinder Version 5 data	4 km global	Daily Since 1985	Satellite data available from NASA at http://poet.jpl.nasa.gov/
SST proxy	AusCore	From 10 *Porites* colonies on	1746-1982	Data from coral cores (Lough & Barnes 1997). Contact Janice

Variables	Dataset	Where	When	Information and accessibility
		Great Barrier Reef		Lough (j.lough@aims.gov.au) at AIMS for details
Temperature, nitrate	Maria Island Coastal Station Data	Maria Island, east coast of Tasmania	Monthly, Since 1944	Surface and subsurface data from CSIRO Marine and Atmospheric Research (CMAR). Data freely available via Data Trawler at http://www.marine.csiro.au/warehouse/jsp/loginpage.jsp
Wind	QuickScat	Global 0.25º	Daily Since 1999	Satellite data available freely from NASA at http://poet.jpl.nasa.gov/
Sea Level	Australian Baseline Sea Level Monitoring Project	65 Australian Ports, longest is Sydney	Various Since 1885	Data available on request from http://www.bom.gov.au/oceanography/
3D ocean model hindcasts	Bluelink (BRAN1)	Australian region 0.25º	Since 1992	Data available on request from David Griffin (david.griffin@csiro.au) at CMAR

5. THE WAY FORWARD: MODELLING CLIMATE IMPACTS

Anthony J. Richardson and Thomas A. Okey, CSIRO Marine and Atmospheric Research

In view of the evidence of climate change impacts on species within Australia and the dramatic and widespread verification from elsewhere in the world, there is growing research on modelling the potential future effects of change. Models and analytical tools provide the capability of predicting the future effects in terms of the diversity, community composition and species interactions.

Climate impacts modelling is much better developed in terrestrial than marine systems. There have been large research programmes focusing on changes in community composition, distribution both horizontally and in altitude, and species' physiological responses. Much of the terrestrial impacts modelling has shifted toward a mitigation phase, whereas in the marine environment, modelling is still focused on understanding potential consequences of climate change. There have been some recent highlights in the literature describing how warming enhances the stratification of the global oceans leading to changes in primary productivity (Sarmiento et al. 2004), and detailing how acidification of the world's oceans will cause organisms with calcareous structures, such as corals and pteropods, to dissolve (Orr et al. 2005).

Relatively little modelling work has been done on species within Australian waters; there has been no large-scale investigation of potential impacts of climate change on the diverse and unique fauna of the region. The only group that has been investigated extensively in terms of the potential implications of climate change are the tropical hard corals, a fact attributable to the iconic status of the Great Barrier Reef. Knowledge of future changes in abundance and distribution of marine species is imperative for marine planners and managers tasked with conserving biodiversity, locating marine protected areas, managing tourism associated with cetaceans and turtles, and implementing management plans for the sustainable use of marine resources and indigenous harvesting. The capacity to make predictions gives policy makers and regional planners confidence to implement or adapt current policy instruments, identify critical thresholds of climate variables for important biomes, develop and test key indicators of change, and highlight sensitive species, communities and ecosystems most under threat (Howden et al. 2003).

There are many modelling approaches available, and this report is not intended to be comprehensive, but will focus on those approaches that can be most usefully to the Australian marine environment in the short to medium term. A gradation of modelling approaches exist (**Figure 5-1**), from those that are purely descriptive in nature (correlating the current distribution of a species with its environment) to those that are more mechanistic (incorporating ecological and physiological mechanisms that determine the response of an organism to its environment). These approaches are not independent, and hybrid modelling versions are possible. Models that relate species, communities and ecosystems to their present environment, whether descriptive or mechanistic, can be forced by output of key physical variables such as temperature from global climate models (GCMs) simulating future conditions. GCMs are run under various scenarios of population growth and industrialisation of society, producing a range of potential futures. The approaches are summarised in **Table 5-1**, together with their advantages and disadvantages.

Given the complexity of marine ecosystems and our current state of knowledge, a suite of modelling approaches is recommended, with no one approach being best for all situations. Although it is likely that some of the approaches will be easier and quicker to apply than others (e.g. climate envelopes), we recommend that they be performed in concert for several reasons. First, during their implementation, each modelling approach will highlight different gaps in data availability and our process understanding in areas such as physiology and species interaction, and it is the suite of approaches together that will drive science forward the most. Second, it is not obvious beforehand which approach will prove most conducive to predicting future changes, and it is likely that each will inform some aspects that the others will not. Last, each has different levels of complexity and data requirements, so the descriptive models (e.g. climate envelopes) will provide quick, broad-scale, first-approximations to climate impacts, whereas the finer-scale mechanistic models (e.g. population models) are more labour-intensive and data-intensive, but may provide more-realistic assessments of climate impacts.

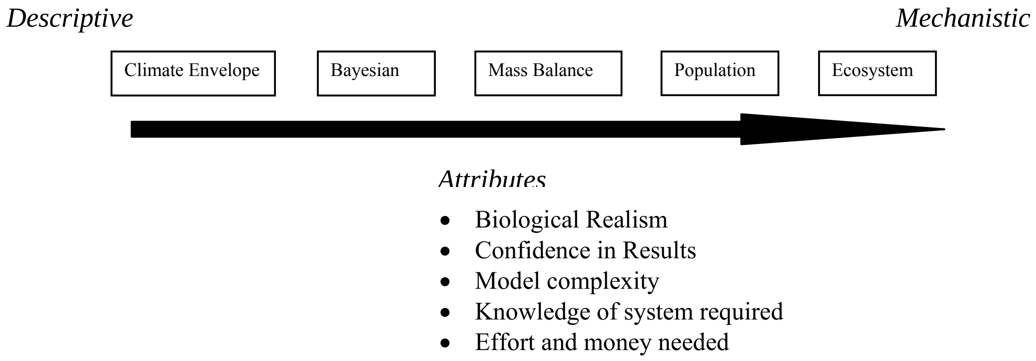

Figure 5-1. The modelling approaches described represent a continuum from descriptive to mechanistic methods. Attributes that vary along this continuum are highlighted.

1. Climate Envelopes

These are the conceptually simplest and easiest models to apply. This approach involves parameterising a statistical model of the current distribution of a species in terms of environmental conditions. Underlying this approach is that climate is the key driver of a species distribution and abundance. This is the central premise of biogeography and evidence from the fossil record and from recently observed changes in species distributions (Walther et al. 2002) show that changing climate has an overwhelming influence on species' range expansion and contraction. This approach has been applied extensively in the terrestrial environment (e.g. Berry et al. 2002; Pearson & Dawson 2003). In Australia, bioclimate envelopes have been applied to many terrestrial species of vegetation such as eucalypts (Hughes et al. 1996), wattles (Pouliquen-Young &Newman 2000), and grasses (Chapman & Milne 1998), as well as insects including butterflies (Beaumont & Hughes 2002) and leaf miners (Johns & Hughes 2002). Bioclimate envelopes have not yet been applied widely in marine systems and to our knowledge there are no published studies for Australian species.

Because of their simplicity, the climate envelope approach has engendered considerable debate over their realism. The debate centres around two issues. First is that biological interactions such as grazing, predation, competition, and facilitation are not included in the models, although these processes probably dominate at relatively small spatial and temporal scales. Climate is likely to be the key population driver at large time and space scales (see **Figure 5-2**). Second is that modes of dispersal can be critical to the distribution of species, so that the distribution of many terrestrial plants, for example, may be more related to the impact of climate change on insect pollinators rather than the direct impact on plants themselves. This may not be as critical in the marine environment, where species are not generally dependent upon other species for cross fertilisation and dispersal.

The bioclimate approach provides a first approximation over a larger spatial scale when detailed mechanistic understanding of the species in question is lacking, and when a large number of species is investigated. At this stage of marine climate impacts research in Australia, where detailed information on the population dynamics of most species is rudimentary or lacking, climate envelopes are a fruitful initial research approach. A suite of environmental variables (sea surface temperature, winds, mixed layer depth) that are available from GCMs can be used to describe climate envelopes. As species distributions are likely to be related non-linearly to these environmental variables, flexible non-linear approaches such as generalised additive and linear models, and artificial neural networks are required. For species where only presence/absence data is available, logistic generalised additive modelling would be useful. Initial predictions can be subsequently refined with more mechanistic models.

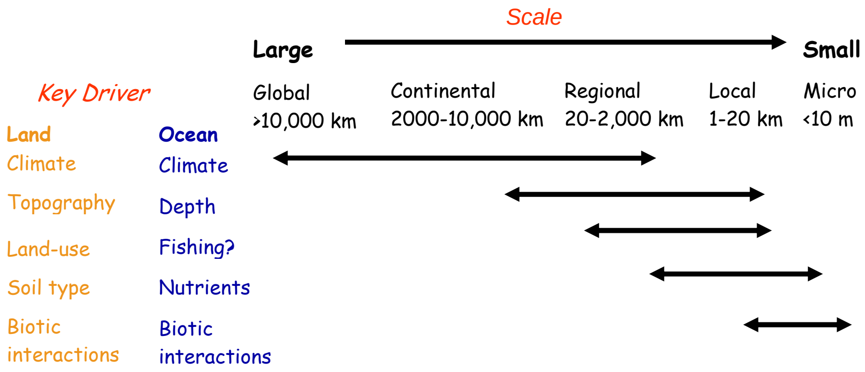

Figure 5-2. Scales of variation in the terrestrial and marine environment and the key drivers.

2. Mass-balance Ecosystem Models – Ecopath, Ecosim and Ecospace

Climate change impacts on species, functional groups, and whole communities will manifest as direct effects on species physiology, phenology, and distributions, but it will also manifest as indirect effects on the biological interactions of a species, which are principal shapers of populations and communities. Thus many climate change impacts in individual populations will have cascading effects throughout the community, the magnitude of which depends on the nature and strength of interactions among connected functional groups. For this reason, a cataloguing of predicted functional responses of individual populations to climate change cannot capture the response of the biological community as a whole without a modelling tool that accounts for the trophodynamic flows in the ecosystem.

The broad ecological impact of climate change can be estimated using the whole food web trophodynamic modelling suite Ecopath with Ecosim and Ecospace. This modelling tool has three complimentary modules: (1) Ecopath is a static mass-continuity description, or accounting, of trophic flows in any given ecosystem and time period using biomass as a currency. It is a food web model in which all species in the system are aggregated into functional groups whose biomasses, production rates, consumption rates, physiological efficiencies, and diet compositions are estimated and specified, and includes flows to and from fisheries; (2) Ecosim uses information in Ecopath dynamically so that temporal changes in mortality or other physiological rates can be specified to simulate impacts of changes in fisheries exploitation or environmental changes, or both simultaneously; and (3) Ecospace enables the expression of Ecosim in a spatially-explicit form for the spatial exploration of biological impacts of an environmental or fisheries change.

Ecopath with Ecosim models are the global standard for trophodymanic models for the assessment of fisheries impacts, with hundreds of practitioners and models around the world. The software for this approach is freely available, transparent, and accessible to anyone (www.ecopath.org), and thus can be used on a variety of research and educational levels. There is a large body of published research documenting the use of this approach in marine ecosystems (e.g. Okey & Pauly 1999, Okey et al. 2004a, Okey et al. 2004b, Okey & Wright 2004), and the approach has been applied to several Australian marine ecosystems to explore impacts of fishing (Bulman et al. 2002; Goldsworthy et al. 2003, Gribble 2003, Fulton & Smith

2004). The Ecopath with Ecosim modelling approach is continually refined by experts, and it is currently entering a phase of explicit incorporation of climate impacts capabilities. General information about the approach is provided by the architects (Christensen & Pauly 1992, Walters et al. 1999, Pauly et al. 2000, Christensen & Walters 2004). Examples of using the approach to estimate climate-related impacts are beginning to emerge (Watters et al. 2003, Okey et al. 2004b, Aydin et al. 2005, Booth & Zeller 2005, Heath 2005, Araujo et al. 2006).

There are four general approaches that are fruitful for characterising climate change impacts using the Ecopath with Ecosim modelling approach:

(1) constructing and balancing future Ecopath models using estimated biomasses and physiological rates for a future scenario, information from climate envelope and other biophysical models, and comparing the projected to the present day system,

(2) producing a time series of fitting error terms that represent non-fisheries impacts (e.g. environmental change) for comparison to integrated ocean climate indicators,

(3) forecasting change using Ecosim based on estimated responses of functional groups to particular scenarios of change,

(4) explicitly integrating functional response models within the Ecopath with Ecosim modelling approach.

The form of the new Ecopath climate modelling system (Ecoclim) will likely include a combination of these approaches, and will require considerable information including the output of other climate impacts modelling approaches. A combination of these approaches, based on the availability of information and resources, will provide a practical approach to assessing the impacts of climate change on Australia's marine ecosystems.

Given the information constraints of such models, the approach will need to be designed in parallel with climate impacts monitoring programs that track key indicators that ideally are central to the model structure and function.

3. Ecosystem models

With our improved understanding of the marine ecosystem and the technological advancement of computing and numerical techniques, it has been possible in recent years to model some of the complexity in marine ecosystems (Allen et al. 2001). Our view of the pelagic marine ecosystem over the last few decades has expanded from one dominated by a simple linear food chain from large phytoplankton through copepods to fish, to one where there are many alternative pathways with microbes, gelatinous zooplankton, and considerable coupling between the pelagic and benthic systems (Azam et al. 1983). Marine ecosystem models can now capture this complexity.

Recently, ecosystem models have been coupled to hydrodynamic general circulation models, capturing the high spatial and temporal variability of ecosystem dynamics (Skogen & Moll 2000; Zavatarelli et al. 2000). Models of benthic biota (Blackford 1997) have also been built and led to the development of coupled bentho-pelagic models whereby the role of nutrient exchange between the two systems can be explored.

With current computing capacity it is now possible to force simple ecosystem models with output from GCMs under various climate change scenarios (e.g. Sarmiento et al. 2004). Moreover, regional ecosystem models embedded within larger-scale models could answer important questions concerning the future change in productivity on the Australian continental shelf and the potential increase in harmful algal blooms and jellyfish in response to climate change. Ecosystem models represent our best understanding of how marine systems as a whole function and coupling these with output from climate system models is likely to provide our best understanding of system response. Developments in process-based ecosystem model simulations will enable us to better understand the effects of climate changes on biodiversity and assess the effectiveness of adaptation and management strategies.

Table 5-1. Types of modelling approaches for assessing climate change implications for biodiversity, examples of models, an explanation of the approach, and their advantages and disadvantages. All these models, once constructed, can be forced by physical variables output from global climate models (GCMs) to predict impacts on species, communities and/or ecosystems in the future.

Approach	Examples	Explanation	Advantages	Disadvantages
Climate Envelope	Off-the-shelf models (e.g. BIOCLIM, CLIMEX) Statistical Modelling (Generalised linear models, generalised additive models, artificial neural networks)	Climate envelope approaches investigate relationships between the distribution/abundance of a species and its existing environmental domain. They then predict changes in distribution/abundance under an altered climate.	• Off-the-shelf models user friendly, although none have been used for the marine environment • Relatively easy and quick • Simple conceptually • Good on regional and basin scale	• Not ‘packaged’, so requires statistical understanding • No mechanistic understanding gained • Poor on local scale • Does not include biological interactions • Artificial neural networks are opaque to understanding • Key assumptions include that data represent entire habitat, distribution is determined principally by climate, and the current distribution is at equilibrium
Bayesian		Bayesian approaches are used in conjunction with other models.	• Suitable when there is high uncertainty • Can be useful for policy and science because Bayesian approaches force users to think about nature of data and questions	• Approaches not generally well understood and can involve complex statistics • Can be computationally demanding
Population Models	IBMs (Individual Based Models)	These models describe the dynamics of a species in an environment based on basic ecological and/or physiological data and understanding. They have been developed to gain an understanding of important species and their interactions. Marine population models are often embedded within 3-D hydrodynamic models.	• Species behaviour and interaction with other species included • Models highlight limitations in understanding of climate–species distribution interactions • These models can incorporate some management options, can explore some adaptations, and can deal with range of interacting factors	• Considerable species knowledge needed that is not available for most marine species • Models may be limited by available data • Considerable research effort needed • Users require an understanding of ecological interactions
Mass Balance Models	ECOPATH with ECOSIM and ECOSPACE	This is the global standard for marine trophodynamic models. ECOPATH is a static mass-continuity description of trophic flows using biomass. ECOSIM specifies information in	• Free and already highly developed • Has some biological realism and includes higher trophic levels such as fish	• Has not been used extensively for climate change impacts work • Not vertically explicit • Is not directly connected to hydrodynamic models

Approach	Examples	Explanation	Advantages	Disadvantages
		ECOPATH dynamically, so that temporal changes in mortality or other physiological rates can be specified. ECOSPACE enables the expression of ECOSIM in a spatially-explicit form.	• ECOPATH can be used to assess the validity of future ecosystem states predicted from other modelling approaches • ECOSIM allows physiological rates to be changed with climate change • ECOSPACE can be used to explore impacts of changes in the distributions of biomasses of each functional group based on how they interact with each other spatially • Incorporates some management options in terms of fisheries	• Representation of climate change impacts relies on incorporation of other modelling approaches (as being developed: Ecoclim)
Ecosystem Models	NPZ (Nutrient, Phytoplankton, Zooplankton) models	NPZ models simulate the changes in biomass of phytoplankton and zooplankton components of the marine ecosystem. They are often embedded within a dynamic, 3-D hydrodynamic model.	• Biologically realistic • Spatially explicit vertically and horizontally • Linked to physical models describing water mass movements that are likely to be affected by climate change • Applicable to most of the ocean • Describes base of foodweb in all but deep, chemotrophic systems • Can incorporate management options	• Complex, with many (often hundreds) of parameters • Difficulty in including higher trophic levels • Considerable research effort needed

6. RECOMMENDATIONS FOR FUTURE RESEARCH, MODELLING AND MONITORING

This review has identified a number of areas in which additional information is required in order to better predict the impacts of climate change on marine species and habitats.

6.1 Key questions to guide future research

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

6.2 Modelling recommendations

Modelling and data collection are required to address the research areas indicated by the key questions shown above. , as outlined in the following sub-sections.

- We recommend that bioclimatic envelopes are a good broad-scale approach for studying marine climate impacts, and can be applied to many Australian marine species immediately. This approach is relatively straightforward, quick to produce and is a good first approximation for the potential future distribution and abundance of marine species under future climate scenarios. Output from such models can then be used to inform more complex mechanistic models. Well-studied groups such as fish (the Codes for Australian Aquatic Biota database) or seagrasses could be the initial foci. There will probably be only a limited number of groups for which we can produce credible climate envelope models, based on data availability and knowledge of ecological processes, but with further monitoring and research these can rapidly be expanded. Species which may be useful as indicator species for climate change or species which are commercially or ecologically important but on which little information is available should be the focus of future monitoring programmes. These include plankton and rocky shore fauna. Output from this approach will be easily interpretable 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.

- Given the functional simplicity of climate envelope models, coupling climate envelope models with more mechanistic models that incorporate some process understanding of density dependence and dispersal will deliver more realistic predictions. This will require considerable knowledge of species’ life-history and ecology and is challenging even for relatively well-studied groups but fish, corals and seagrasses are good candidates. Such models will provide more realistic outputs than climate envelope models, and will in addition highlight gaps in our understanding of ecological processes. Although climate envelope models provide a broad view of potential impacts, more realistic simulation models are necessary for adaptive management strategies.

- Another form of mechanistic model is the population dynamic model. There are many well-established fisheries models that can be adapted to incorporate processes influenced by climate change. Population dynamics models should also be implemented on species that we know are particularly sensitive to climate change. Revised fisheries models will allow us to project future fishery yields for many stocks important to the Australian economy. These can be adapted for non-exploited species such as marine turtles where the sex ratio of hatchlings depends on nest temperature; coccolithophores and corals which dissolve in acidic waters; and harmful algal blooms and jellyfish which can increase in abundance with temperature and stratification. Each of these species have a key stage in their lifecycle that is sensitive to climate change, and only a dynamic mechanistic approach will provide robust estimates of impacts.

- Simple mass-balance ecosystem models of future scenarios such as Ecopath in combination with Ecosim and Ecospace should be constructed. This is a well-established and widely used approach, and there are already existing Ecopath models for several regions in Australia. These ecosystem models will not only provide predictions of future ecosystem biomass, species composition, and exploration of future fisheries yield but would also allow for testing the biological realism of outputs from other models.

- Detailed NPZ models with multiple phytoplankton and zooplankton functional groups and forced by output from global climate models should be developed. These models can have a spatially explicit depth component, which is generally lacking in other approaches. NPZ models provide our best predictions of lower trophic level productivity in 3 dimensions in the ocean, as they are directly embedded within oceanographic models. These would allow predictions of how pelagic productivity zones would change in location and intensity in the future, as well as ramifications for higher trophic levels that are attracted to these productive zones. This would enable assessment of the economic implications for the fishing industry. Additionally, output from NPZ models will detail potential changes in the productivity on the Australian continental shelf, and are the best approach to inform the positioning of offshore Marine Protected Areas.

6.3 Monitoring recommendations

Monitoring programs can produce results that reveal climate impacts independently from predictive modelling, but such results emerge slowly whereas combining predictive modelling with monitoring will provide more timely results and insights into climate impacts. Any modelling programme, moreover, requires the monitoring of potential changes in the habitat, species or functional group to intialise, validate and refine models, and to improve predictive capacity. Similarly, modelling programmes can be used to inform monitoring programmes about key species, regions and processes.

1. Present Australian time series that are ongoing should continue to be supported. The past is littered with many discontinued time series that would be very valuable now.

2. Australia is clearly depauparate in many long-term baseline datasets. To supplement existing monitoring projects, priority groups that urgently require observing programmes are presented in **Table 6-1**.

Table 6-1. Biological groups that stand out as good candidates as informative and practical indicators of climate change

Group	Justification
Phytoplankton	Important as primary producers; large changes in distribution, abundance and phenology expected
Zooplankton	Important trophically; large changes in distribution, abundance and phenology expected
Rocky shore macrofauna and flora	Cheap to monitor; easily accessible; changes in distribution and abundances expected
Deep sea corals	Sensitive to climate change; high levels of endemism of associated species; very little known
Soft-bottom benthic fauna	Important trophically; high diversity; likely to be sensitive to changes in primary productivity

Without observation systems for these groups, Australia will not know how climate change is impacting its marine diversity.

7. APPENDICES

Appendix 1. Dimensions of vulnerability and indicators

The rationale for each of the five dimensions selected is briefly discussed below, together with their indicators, the details of the data, and processing to derive the indicator scores. Each of the indicators can be matched to an element of the vulnerability definition (Allen Report, 2005).

Biological dimension (B)
Vulnerability of biodiversity in a region to climate change is related to the integrity and health of that ecosystem (Allen Report, 2005), so that healthy ecosystems are more resilient to exposure to external stressors such as climate. Four indicators were included to represent biodiversity in a domain.

B1*: Number of threatened, endangered and protected species (sensitivity)*
The rationale for including this indicator is that biodiversity in domains with a high number of species that are already threatened may be more sensitive and hence vulnerable to climate change. Data on the number of threatened, endangered and protected (TEP) marine species were sourced from the Department of Environment and Heritage in 2006. The location of these species around Australia was then used to generate a list of species for each domain. Each domain was assigned a rank between 1 (fewest TEP species, lowest vulnerability) and 5 (most TEP species, highest vulnerability).

B2*: Endemism (sensitivity)*
This indicator was included because domains with high endemism may reflect a high number of species adapted to local conditions. This local specialisation may leave these taxa with a relatively poor ability to cope with a rapid change in conditions, as is expected under climate change. The best data available on endemism in a region across many marine species in Australia are the TEP marine species. The number of unique species in each domain was used as an estimate of endemism. Domains with high endemism were rated as most vulnerable.

B3*: Number of introduced marine species (sensitivity)*
Regions with a large number of introduced (non-indigenous) species may already be stressed and thus more vulnerable to climate change than more pristine systems. For example, successful invaders often out-compete native species. The number of introduced marine pest species was obtained from the NIMPIS (*National Marine Pollution Information System*) database, which reports the number of introduced and native species from port surveys around Australia. Although these data come from port surveys, these species can then move more widely into the surrounding marine regions where a variety of detrimental impacts have been documented (see review by Grosholz 2002). Introduced species in these lists include fish, dinoflagellates, worms, hydroids, seastars, barnacles, bryozoans, crabs, chitons, ascideans, oysters, sea slugs, tubeworms, mussels, isopods, shrimp, and macroalgae. The percentage of introduced species (out of all species identified from the port) was used as the measure of non-indigenous species. Domains with a high proportion of non-indigenous species were ranked as highly vulnerable.

B4: *Community uniqueness(sensitivity)*
If a domain has a similar community structure as neighbouring domains, particularly if species can shift to neighbouring areas, then climate change may be less of a threat as neighbouring areas may act as a refuge during times of extreme climate and may also allow recolonisation either from populations shifted into the area or from resident populations. Additionally, if neighbouring areas have similar communities then it is assumed that similar habitats exist so allowing species migrations in the face of climate change. Based on the presence/absence of TEP species in each region, we calculated the Bray-Curtis similarity measure between each

domain. We then calculated the highest similarity for each of the domains; the lowest similarity implies uniqueness and a high vulnerability.

Regional characteristic dimension (R)

A total of four indicators were used to represent the inherent physical characteristics of a region.

***R1**: Total Area (sensitivity)*
Species in small domains are less buffered against climate impacts than larger domains. A small area was rated as highly vulnerable.

***R2**: Proportion of area dependent upon foundation species (sensitivity)*
Foundation species are those that facilitate other biota in a community by providing habitat structure or other fundamental community services (e.g. tropical corals or kelp in temperate areas). Since these foundation species support a diverse community, the presence of foundation species makes a domain vulnerable. Because of the difficulty in calculating the proportion of an area that was dependent upon foundation species, we used the proportion of each domain shallower than 50 m depth as a proxy, assuming most foundation species occur in shallow coastal waters. The obvious exception to this proxy rule is cold-water corals, which are also a foundational habitat, Domains with a high proportion of area shallower than 50 m were assigned a high vulnerability.

***R3**: Poleward boundedness (sensitivity)*
An extension or shift in species' ranges towards the poles is predicted as climate warms, so biodiversity may be less vulnerable to climate change if there are suitable domains to the south. In the case of coastal or shelf-restricted species, once suitable climate space moves further south than the south coast of Australia and Tasmania, there is no more habitat to occupy. Southern domains around the coast of Australia (with no southerly neighbours) were scored as high vulnerability

Climate change dimension (C)

We derived a number of environment indicators that represent the expression of climate change in each domain. All the climate change indicators were calculated from output from the CSIRO Mk3.5 model (Chapter 2, Box 1). It is not possible to make general statements about whether an increase or a decrease in an indicator would be positive or negative for biodiversity, with different species being adapted to different conditions. We have assumed that marine species are adapted to local conditions so that any predicted environmental change is assumed to increase the vulnerability of biodiversity. A total of seven indicators were extracted from the climate model data. The absolute magnitude of change in the selected climate variables (averaged for the period 2065-2075) from the current values (averaged for the period 1995-2005) was scored between 1-5, similar to other indicators, with maximum changes assigned the highest vulnerability. Although there may be considerable variation in these variables within some of the domains (e.g. inshore vs offshore salinity), owing to the broad-scale nature of our analysis we have treated domains as spatially homogeneous.

***C1**: Predicted Sea Surface Temperature (SST) change (exposure)*
SST influences the distribution and abundance of many marine species. Change in SST was calculated as the percent change compared to the present; this was to correct for the difference in the absolute temperature values within each domain. The greatest percentage change was then scored highly.

***C2**: Predicted change in temperature at 500 m (exposure)*
Impacts on deeper components of biodiversity were included in the index through an estimate of temperature change at depth. The absolute percentage change from 1990s to 2070s was

calculated using the average domain temperature at 500 m. The greatest percentage change was then scored highly.

***C3**: Predicted change in mixed layer depth (exposure)*
The mixed layer is the upper wind-mixed layer of the ocean. The depth of the mixed layer influences biological processes at the base of the food chain, such as phytoplankton blooms, as well as constrains the foraging range of higher trophic level species. The absolute percentage change between the two decades was calculated based on the average mixed layer depth (m) in each domain. The greatest percentage change was then scored highly.

***C4**: Predicted change in Incident Solar Radiation (exposure)*
Solar radiation is important for phytoplankton productivity and can harm some species if too intense. This variable is expected to change due to an increase/decrease in cloud cover. The absolute percent change was estimated for each domain. The greatest percentage change was then scored highly.

***C5**: Predicted change in surface currents (exposure)*
Ocean currents influence dispersal and recruitment of marine species, deliver nutrients from other regions, aid migrations, and enhance retention. Changes in the surface circulation may disrupt these processes. Average current strength (cm/s) was calculated for each domain, and large absolute changes from the present were considered detrimental to the domain biodiversity and scored highly. Scores of 1-5 were allocated to the range of percentage change. Using the magnitude of surface currents, rather than including direction, nullifies problems associated with the vector addition of currents.

***C6**: Predicted change in surface winds (exposure)*
Wind is a key driver in coastal upwelling and the subsequent introduction of nutrients from deeper waters into the mixed layer, where biological production occurs. Winds also drive surface currents, and hence impact the dispersal of entrained animals and plants. Strengthening or weakening of winds may lead to higher or lower productivity, depending on the existing wind intensity, direction and interaction with local topography and currents. Average monthly winds from the model runs represent the large-scale forcing only, as diurnal winds and storm activity are not represented. The percentage change in average surface wind strength (m/s) for the present and future period was calculated. A large change was scored as high vulnerability.

Fishing stress dimension (F)

Fishing stress decreases the resilience of populations and communities to the additional stress potentially imposed by climate changes. A total of six indicators were derived to measure this dimension, and will adversely affect the adaptive capacity element of vulnerability as defined by Allen Report (2005). For indices of fishing stress, a high score means higher vulnerability to climate change.

***F1 and F2**: Habitat impacts index and bycatch impacts index (adaptive capacity)*
Two indices, reflecting habitat impacts and bycatch impacts, are the 2002-2005 average annual fishing effort per unit area for each gear type in each domain weighted by ratings of gear type impact (Chuenpagdee et al. (2003), Morgan & Chuenpagdee (2003)). Specific Australian fisheries sectors were adapted to ten gear type categories for this analysis: bottom trawl, dredge, bottom gillnet, midwater gillnet, pots and traps, pelagic longline, bottom longline, midwater trawl, purse seine, and hook & line. We used the mean of the two habitat impact ratings (physical and biological) for each gear type and the mean of the five bycatch impact ratings (shellfish & crabs, finfish, sharks, marine mammals, seabirds & turtles) for each gear type to derive the habitat and bycatch impacts indices. High values of these indices represented high vulnerability.

***F3**: Overfishing index (adaptive capacity)*

The overfishing index is the number of stocks classified as overfished or subject to overfishing in each of the marine domains. Stocks and status were taken from (Caton & McLaughlin 2004) and the locations of those stocks were then scored according to presence in each domain. A higher number of overfished stocks in a domain reflects higher vulnerability.

***F4**: Commercial fishing effort index (adaptive capacity)*
The number of hours of fishing effort by Australian Government-managed fisheries for the period 2001-2005 was totalled for each domain. Data was obtained from the CSIRO copy of the Australian Fisheries Management Authority database. A high number of fisheries was assumed to increase vulnerability of biodiversity in the domain to climate change.

***F5**: Number of commercial fisheries (adaptive capacity)*
The number of Australian Government commercial fisheries in each of the domains was counted based on the distribution of fishing effort over the four-year period ending in 2005. Many domains, e.g. South-east, contain more than one fishery (see Appendix 2). Data were obtained from the CSIRO copy of the Australian Fisheries Management Authority database. A high number of fisheries is assumed to increase vulnerability of biodiversity in the domain to climate change.

***F6**: Recreational fishing effort index (adaptive capacity)*
The recreational fishing effort index is the relative recreational fishing effort among domains, and was estimated by allocating the estimated number of recreational fisher days among Domains based on ratios of recreational fishing households between and among sub-regions (see Lyle et al. (2003)). Estimates of thousands of recreational fisher days were expressed per square degree. Domains with intense effort were assigned a highly vulnerable rating.

Anthropogenic stress dimension (A)

Other anthropogenic stressors increase the sensitivity of populations and communities to the additional stress potentially imposed by climate changes. A total of eight indicators were derived to measure this dimension and, as with the fishing stress dimension will adversely affect the adaptive capacity element of vulnerability as defined by Allen Report (2005). For indices of anthropogenic stress, a high score means higher vulnerability to climate change.

A1*: Coastal Development (adaptive capacity)*
Coastal development will stress ecosystems through increased usage of marine habitat, reduction in habitat through coastal engineering, oil spills and mechanical damage such as dredging shipping channels. Coastal development was determined by population living with 200 km of the coast sourced census records for 1996 from the Australian Bureau of Statistics website (www.abs.gov.au). Estimates of total population (in millions) per domain were converted to the 1-5 scale with 5 representing highest populations.

A2, A3, A4 *Organic Compounds, Synthetic Compounds, Heavy Metals (adaptive capacity)*
Data on the emission points and volume (in total kg) of each of three pollutants, viz. organic compounds, chemical compounds and heavy metals, for the years 2001-2002 were obtained from the National Oceans Office Marine Atlas. They were originally sourced from the Department of Environment and Heritage Australia's National Pollution Inventory. Elevated levels of pollutants were then scored highly.

A5 *Chemical dump sites and tracks (adaptive capacity)*
Data on the chemical dumps and tracks in Australian marine waters were obtained from the National Oceans Office National Marine Atlas, and originated from the Australian Hydrographic Service. Domains with high numbers were scored highly.

A6 *Ship visits (adaptive capacity)*

Ship visits were obtained from the National Oceans Office National Marine Atlas, and originated from state authorities. High ship visitation rates may increase likelihood of introducing exotic pests which can have devastating consequences for native species.

A7 *Oil and Gas Wells (adaptive capacity)*
Locations of offshore wells drilled in Australian waters for the purposes of oil and gas exploration and development were obtained from the National Oceans Office National Marine Atlas. Original data was sourced from Geosciences Australia. Domains with large numbers of oil and gas well were then rated as highly vulnerable.

A8. *Seismic Surveys (adaptive capacity)*
Seismic surveys have been implicated in the deaths of some marine mammals, and even regeneration abilities of seagrasses. Seismic survey frequency data were obtained from the National Oceans Office National Marine Atlas, and originated from state authorities. Domains with intense seismic survey levels were then scored highly.

Appendix 2. Indicator values and scores

Appendix 2. Indicator values and scores in each dimension used to develop the index of vulnerability for the Australian large marine domains. Numbers in brackets represent actual values.

Dimension	Indicator	Name	Northern	North Eastern	North Western	Western Central	Eastern Central	South Western	South Eastern
Biological	B1	Threatened, endangered & protected (TEP) species	2 (131)	4 (154)	1 (122)	3 (140)	5 (165)	1 (127)	1 (128)
	B2	Number of endemic demersal slope fish	1 (32)	5 (94)	5 (108)	1 (31)	2 (56)	1 (26)	2 (52)
	B3	% introduced species per port	1 (0.7)	1 (3.1)	1 (1.5)	5 (14.0)	3 (6.5)	4 (9.2)	3 (7.2)
	B4	TEP uniqueness	1 (0.7)	1 (0.17)	4 (0.27)	4 (0.27)	5 (0.30)	2 (0.19)	2 (0.19)
		Final score	1.25	2.75	2.75	3.25	3.75	2.00	2.00
Regional	R1	Area (square degrees)	3 (67.9)	1 (109.2)	3 (77.4)	4 (50.1)	3 (61.0)	1 (104.6)	1 (124.4)
	R2	Foundational Area (% less than 50 m)	5 (38.6)	1 (10.3)	2 (15.6)	1 (7.3)	1 (4.4)	2 (11.7)	1 (4.2)
	R3	Poleward boundedness	1	1	1	1	1	5	5
		Final Score	3.00	1.00	2.00	2.00	1.67	2.67	2.33
Climate change	C1	% change in sea surface temperature	4 (0.56%)	4 (0.57%)	2 (0.50%)	2 (0.48%)	5 (0.61%)	1 (0.43%)	4 (0.56%)
	C2	% change in temperature at 500 m depth	5 (0.25%)	5 (0.25%)	5 (0.26%)	5 (0.26%)	5 (0.23%)	1 (0.06%)	5 (0.25%)
	C3	% change in Mixed Layer Depth	1 (0.38%)	5 (6.78%)	1 (0.97%)	2 (2.72%)	4 (4.66%)	4 (4.67%)	1 (1.41%)
	C4	% change in Incident Solar Radiation	2 (1.31%)	2 (1.36%)	5 (2.68%)	1 (0.79%)	2 (1.39%)	2 (1.49%)	1 (1.05%)
	C5	% change in Surface currents	1 (11.06%)	1 (4.44%)	2 (22.98%)	1 (11.24%)	1 (1.20%)	5 (56.07%)	1 (5.66%)
	C6	% change in Surface winds	1 (5.34%)	1 (2.17%)	5 (25.80%)	1 (6.51%)	5 (21.82%)	2 (11.49%)	1 (3.30%)
		Final Score	3.45	3.89	3.48	2.76	4.35	1.65	3.31
Fishing	F1	Fisheries gear impact – habitat	5	1	1	1	2	2	3
	F2	Fisheries gear impact – bycatch	5	1	1	2	3	2	3
	F3	Overexploited fisheries	3 (6)	2 (4)	1 (0)	1 (1)	1 (1)	3 (6)	5 (12)
	F4	Number of fisheries hours	5 (463324)	1 (37306)	1 (31976)	1 (43414)	3 (227436)	1 (105882)	5 (502320)
	F5	Number of AFMA fisheries	1 (3)	2 (6)	1 (3)	2 (5)	5 (11)	4 (10)	5 (12)
	F6	Recreational fishing index (1000s days per degree)	1 (9.4)	2 (39.7)	1 (2.2)	2 (25.9)	5 (112.8)	2 (35.6)	2 (28.7)
		Final score	3.39	1.57	1.01	1.32	3.17	2.04	3.84
Anthropogenic	A1	Population within 200 km of coast (1996)	1 (145241)	1 (653253)	1 (56251)	1 (1388061)	5 (8538423)	2 (2010081)	3 (5028719)
	A2	Organic Compounds	1	3	5	4	4	3	3
	A3	Chemical Compounds	5	4	5	5	2	3	3
	A4	Heavy Metals	1	3	5	3	1	5	5
	A5	Chemical Dumps	1	3	1	2	5	1	5
	A6	Ship Visits (introduced species vector)	2	4	3	1	5	4	4
	A7	Oil and Gas Wells	4	1	5	2	1	2	4
	A8	Seismic surveys	4	1	5	3	2	2	4
		Final score	2.38	2.50	3.75	2.63	3.13	2.75	3.88
Overall	29	Score (average for all dimensions)	2.68	2.33	2.60	2.43	3.21	2.28	3.07
		Rank - 1 most vulnerable, 7 least vulnerable	3	6	4	5	1	7	2

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