Australian Government

Department of Climate Change

IMPLICATIONS OF CLIMATE CHANGE FOR AUSTRALIAN FISHERIES AND AQUACULTURE A PRELIMINARY ASSESSMENT

National Research

FLAGSHIPS

Climate Adaptation

CSIRO

Implications of Climate Change for Australian Fisheries and Aquaculture: a preliminary assessment

Alistair J. Hobday, Elvira S. Poloczanska, Richard J. Matear (eds)

Important Notice – please read

This document is produced for general information only and does not represent a statement of the policy of the Australian Government. The Australian Government and all persons acting for the Government preparing this report accept no liability for the accuracy of or inferences from the material contained in this publication, or for any action as a result of any person's or group's interpretations, deductions, conclusions or actions in relying on this material.

Citation

Preferred way to cite this publication:

Hobday, A. J., E. S. Poloczanska, and R. J. Matear (eds) (2008). Implications of Climate Change for Australian Fisheries and Aquaculture: a preliminary assessment. Report to the Department of Climate Change, Canberra, Australia. August 2008.

Citation for individual chapters

Hobday, A., Poloczanska, E., Matear, R. (2008). Introduction: Climate and Australian Fisheries and Aquaculture. In *

Preston, N., and Poloczanska, E. S. (2008) Aquaculture. In *

Okey, T. A., and Poloczanska, E. S. (2008) Northern Fisheries. In *

Thresher, R., Klaer, N., Lyne, V., Bax, N., Rintoul, S. (2008) South-east Demersal Fisheries. In *

Matear, R. J., Hobday, A J., Caputi, N. (2008) Western Fisheries. In *

Hobday, A. J., and Young, J. (2008) Pelagic Fisheries. In *

Poloczanska, E. S., Leaper, R. and Matear, R. J. (2008) Sub-Antarctic Fisheries. In *

* Hobday, A. J., E. S. Poloczanska, and R. J. Matear (eds). Implications of Climate Change for Australian Fisheries and Aquaculture: a preliminary assessment. Report to the Department of Climate Change, Canberra, Australia. August 2008.

Front cover image credits

From top:
1. Ship Silhouette, Open Water (CSIRO)
2. Southern bluefin tuna longlining fleet (CSIRO)
3. Jack mackerel (Graham Blight)

Title page image credit

1. Fishing boats (Alistair Hobday)

Preface by the Australian Government

Climate change will increasingly impact upon Australian fisheries and aquaculture over coming decades. *A National Approach to Addressing Marine Biodiversity Decline,* endorsed by the Natural Resource Management Ministerial Council in April 2008, recognises climate change as one of five key broad-scale threats to marine biodiversity. Changes to environmental variables such as ocean temperature, currents, winds, nutrient supply, rainfall, ocean chemistry and extreme weather conditions are likely to have significant impacts on marine ecosystems. As a result, climate change will pose challenges and present opportunities to the industries that rely on the marine environment.

In its Fourth Assessment Report 2007, the IPCC found that 'warming of the climate system is unequivocal' and that levels of greenhouse gas emissions such as carbon dioxide, methane and nitrous oxide in the atmosphere have increased markedly as a result of human activities since 1750. These changes have altered the energy balance in the atmosphere, resulting in a warming effect.

Recent Australian projections of climate change provide further details to those provided in the IPCC Fourth Assessment Working Group II report. In its *Climate change in Australia: technical report 2007*, CSIRO and the Bureau of Meteorology (BoM) concluded that by 2030, the best estimate of sea surface temperature rise is 0.6 – 0.9 °C in the Southern Tasman Sea and the north-west shelf of Western Australia, and 0.3 - 0.6°C elsewhere.

The Australian Government commissioned CSIRO to review the potential impacts of climate change on Australia's fisheries and aquaculture. Completed before the release of the *Climate change in Australia: technical report 2007*, the report provides a preliminary assessment of the state of knowledge of the implications of climate change for fisheries and aquaculture in Australia.

This review identifies that there are likely to be significant climate change impacts on the biological, economic, and social aspects of Australian fisheries and finds that there is little consolidated knowledge of the potential impacts of climate change. Both positive and negative impacts are expected, and impacts will vary according to changes in the regional environment: south-east fisheries are most likely to be affected by changes in water temperature, northern fisheries by changes in precipitation, and western fisheries by changes in the Leeuwin Current.

There may be new opportunities for some wild fisheries where tropical species shift southward. There will also be many challenges, such as that faced by the Tasmanian salmon aquaculture industry due to Atlantic salmon being cultivated close to their upper thermal limits of optimal growth. Nevertheless, the report also highlights that there is potential for adaptation measures to be employed by the industry.

The report also notes the need for fisheries and aquaculture management policies to better integrate the effects of climate variability and climate change in establishing harvest levels and developing future strategies. This will enhance the resilience of marine biodiversity and the adaptive capacity of the fisheries and aquaculture industries.

Findings from this review will help inform the development of a National Climate Change and Fisheries Action Plan, a priority action of the National Climate Change Adaptation Framework endorsed by the Council of Australian Governments in 2007. The Action Plan is being developed by the Department of Agriculture, Fisheries and Forestry in consultation with fishery managers and the commercial, aquaculture and recreational fishing sectors, and is due for completion in 2008. The objective of the Action Plan is to assist fishers from all fishing sectors to adapt to unavoidable impacts of, and, where relevant, mitigate the effects of their operations on, climate change.

The Australian Government is investing $126 million over five years in climate change adaptation policies, programs and research, including the development of national adaptation research plans for key sectors. Through the National Climate Change Adaptation Research Facility, a National Adaptation Research Plan for Marine Biodiversity and Resources will be developed in 2008 to provide a national statement of research priorities that need to be addressed to enhance the capacity of marine and fisheries managers to adapt to climate change.

In addition, the Australian Government is providing $130 million over four years to help primary producers adapt and respond to climate change through the Australia's Farming Future initiative.

A further $44 million is being invested in a CSIRO Climate Adaptation Flagship. These initiatives will position Australia to manage risks arising from the impacts of climate change and will rely on strong partnerships between governments and decision makers in industries and communities in all sectors.

Acknowledgements

Table of Contents

List of Figures

List of Tables

Executive Summary

Fisheries and aquaculture are important industries in Australia, both economically (gross value over A$2.12 billion in 2005/06) and socially. Climate change is likely to bring a range of both opportunities and challenges to the sector, but overall it would seem that it will pose some very significant risks to the sustainability of fisheries and aquaculture in Australia. There is, however, little consolidated knowledge of the potential impacts. Australian fisheries and aquaculture management policies do not currently incorporate the effects of climate variability or climate change in setting harvest levels or developing future strategies, although the new Australian Government Harvest Strategy Policy implicitly accounts for a changing baseline climate.

The evidence for climate change impacts on marine fisheries has been largely inferred from studies of climate variability because (i) climate change scenarios for the coastal and pelagic environments have until recently lacked the spatial resolution necessary for most biological studies, and (ii) most fisheries and their captured species are not amenable to experimental manipulation. Australia lacks baseline information on many fished stocks to assess climate impacts. Faced with the very limited research on how climate change may affect Australian fisheries, the first step is to understand current relationships between the climate and marine species. This review summarises the latest information on the link between climate and exploited marine species to identify possible climate change impacts.

The expected changes in the oceans surrounding Australia are described based on output from the CSIRO Mk3.5 model for the decades 2030 and 2070. The key variables expected to drive the climate change impacts on fisheries and aquaculture are changes in temperature, ocean currents, winds, rainfall, sea level, ocean chemistry and extreme weather conditions. The major fisheries examined in this review were considered within sectors; Aquaculture, Northern Fisheries, South-east Demersal Fisheries, Western Fisheries, Pelagic Fisheries and Sub-Antarctic Fisheries. Summary boxes at the end of each section highlight the critical findings. Australia has a number of other fisheries that were not considered in this review: general climate impacts in a region will likely have impacts on these fisheries too. Stakeholders may explore likely impacts to these other fisheries by considering the general physical changes in the region together with documented impacts on similar fisheries in the region and elsewhere.

From this review it is apparent that climate change will impact the biological, economic and social aspects of many fisheries. Both positive and negative impacts are expected, and this review considers both possibilities. Fisheries will be impacted differently according to the physical changes in the regional environment, for example, south-east fisheries are most likely to be affected by changes in water temperature, northern fisheries by changes in precipitation, and western fisheries by changes in the Leeuwin Current. With regard to socio-economic impacts, aquaculture industries have considerable adaptation potential via selective breeding, regulating the environment, and new species opportunities. Wild fisheries will see increased opportunity where tropical species move southward, while for southern fisheries, reconciling non-climate threats with increasing temperature will require proactive management. Management structures and policies that account for climate change will allow most flexibility in adapting to future patterns.

In future, information on the biological relationships with climate variability must be collected to give insight into the impacts of climate change on fisheries and aquaculture. With additional information, assessments of future impacts can be made with greater confidence and management responses can be justified to sometimes reluctant stakeholders. Retrospective analyses, including paleo-ecological studies, will continue to be crucial in resolving physical-biological relationships, with ocean models providing previously missing or unattainable environmental data. The research partnership between climate modellers and fisheries and aquaculture scientists must be fostered to ensure that biologically relevant information, at desirable spatial and temporal scales, will be available from the climate models.

Immediate progress with maximum reward can be made by undertaking focused regional studies. The following areas may provide rapid insight and generate improved understanding of climate change threats, opportunities and adaptation strategies.

- Investigation of climate impacts on south-east demersal fisheries. The relatively long biological time-series already in existence and documented range changes suggest this is an area where clear impact will occur. The south-east area is also the region where climate models indicate rapid warming (Tasman Sea warming), and considerable social disruption would occur if key fisheries were affected. It is important to consider the potential for mitigation or adaptation to any anticipated change. Fisheries and the management approach in this region are also undergoing major restructuring and have shown willingness to consider climate information in setting catch levels.

- Investigation of climate impacts on western rock lobster. The recruitment link currently used to estimate future catch is a statistical relationship whose mechanism is not fully understood. If climate change leads to decoupling of this link, such that the adult biomass is no longer well predicted by larval settlement, then the current management regime may be compromised, and a valuable and high-profile industry impacted. Elucidating the role of climate variability in this fishery would support a sustainable future.

- Investigation of socio-economic impacts of climate on fisheries and aquaculture. A regional focus study, such as on the Eastern Tuna and Billfish Fishery, where environmental variability is a key driver of fishing effort, or on an aquaculture industry such as salmon farming, would allow development of integrated models predicting how the socio-economic impacts of climate change will be felt. This challenging area would require partnerships between biologists, social scientists, economists and ocean modellers from a range of Australian organisations.

- Investigation of changes in productivity around Australia. Current ocean forecasts focus on physical changes; the crucial next step is to forecast change at the base of the food chain. For example, changes in upwelling and mixing may impact regional productivity and thus the range and distribution of key species that occur across a variety of fisheries.

- Investigation of the long-term patterns in distribution and abundance of key species. Studies based on paleo-ecology techniques elsewhere in the world have shown that fluctuations in fish stocks have been dramatic over periods of thousands of years. Knowledge of past response may inform future change, and such approaches may compensate for the lack of long-term historical data in Australia.

While this review has focused on the biological relationships between climate change and fisheries and aquaculture, non-biological impacts were also addressed. Overall, there was a lack of information on non-biological impacts, and in future ecological understanding must be coupled with socio-economic models. This broader focus would provide economic information to support the management response to climate impacts on exploited marine species and to resolving adaptation alternatives. This review, undertaken for the Department of Climate Change, serves as a summary of knowledge – the next step may be to focus in detail, as suggested above, on particular fisheries of high economic or social value, or fisheries with high vulnerability.

Image credit: Elvira Poloczanska

1. Introduction: Climate and Australian Fisheries and Aquaculture

The Australian Fishing Zone (AFZ) is one of the largest in the world, ranging from Torres Strait in the far north to waters adjacent to continental Antarctica, and from Lord Howe Rise in the east to Christmas Island in the west. The gross value of Australian fisheries production was estimated to be A$2.12 billion in 2005-06, of which about 35% is from the aquaculture industry (ABARE 2007). Rock lobster, prawns, abalone and tuna are the most valuable fisheries, accounting for 55% of Australia's gross value of fisheries production in 2005-06. The Australian Government-managed (Commonwealth) fisheries contributed 13% of fisheries production, with major fisheries being the Northern Prawn, Southern Bluefin Tuna and the South East Trawl and Non-trawl Fisheries. Western Australia has the largest gross value of production accounting for 29% of total state fisheries production followed by Tasmania (22%) and South Australia (22%; ABARE 2007).

In the 2006 annual report on the state of Australia's fisheries, the Australian Bureau of Rural Sciences classified 19 of the 97 stocks assessed as either overfished and/or subject to overfishing, 51 as status uncertain, and 27 as not overfished (Larcombe & McLoughlin 2007). The high proportion of stocks classified as uncertain reflects the addition of new stocks not previously classified and the revised classification of some stocks for which assessments were previously thought to be more reliable. The high proportion of uncertainty, especially considering the addition of cumulative pressures associated with a changing climate, highlights the need for reliable assessment information and a growing understanding of complex relationships between fisheries stocks and climate.

The aquaculture industry has been growing steadily; the value of Tasmanian salmon aquaculture increased to A$221 million in 2005-06 (a 65% increase from 2004-05) and new aquaculture industries for abalone and barramundi are expanding rapidly (ABARE 2007). This sector would also be challenged by a changing climate, particularly given the projected sea surface temperature warming hotspot off south-east Australia (Cai et al. 2005) which will impact the Tasmanian salmon industry, among others.

Climate change is likely to bring a range of both opportunities and challenges to the sector, but overall it is likely there will be very significant risks to the sustainability of fisheries and aquaculture in Australia. This review draws together recent information on climate influences on selected marine fisheries and aquaculture ventures in Australia; the impacts on recreational marine fisheries are not considered.

Australian Marine Waters

Australia is bounded at the eastern and western coasts by two southward-flowing ocean currents - the East Australian Current and the Leeuwin Current (Figure 1.1). These major ocean currents carry nutrient-poor water of tropical origin to cooler temperate regions and this southward advection is reflected in the occurrence of tropical marine fauna and flora at normally temperate latitudes. These currents are important drivers of recruitment and abundance of several commercially important species including, for the Leeuwin Current, western rock lobster, scallops, sardines and whitebait (Chapter 5), and for the East Australian Current, tropical tunas (Chapter 6).

Australian waters span both temperate and tropical zones and extend into Antarctic waters, with high endemism in the south and a shared Indo-Pacific fauna in the north. Australian fisheries and aquaculture ventures operate almost everywhere around Australia. The marine communities of temperate Australia have the highest level of endemism of any of Australia's coastal communities. For example, 95% of molluscs and 90% of echinoderms in the Flindersian Province are endemic. These species are already at or close to the poleward limit of the Australian land mass, and many may be lost as the climate continues to warm. Although considerable public emphasis has been placed on the effects of climate change on such iconic ecosystems as the Great Barrier Reef, in fact the greatest losses in marine biodiversity are likely to be in temperate Australia, and the productive ecosystems that support today's nearshore commercial fisheries may well be changed irrevocably. The impacts of climate change will differ among regions, and in all cases the likely impacts are still uncertain.
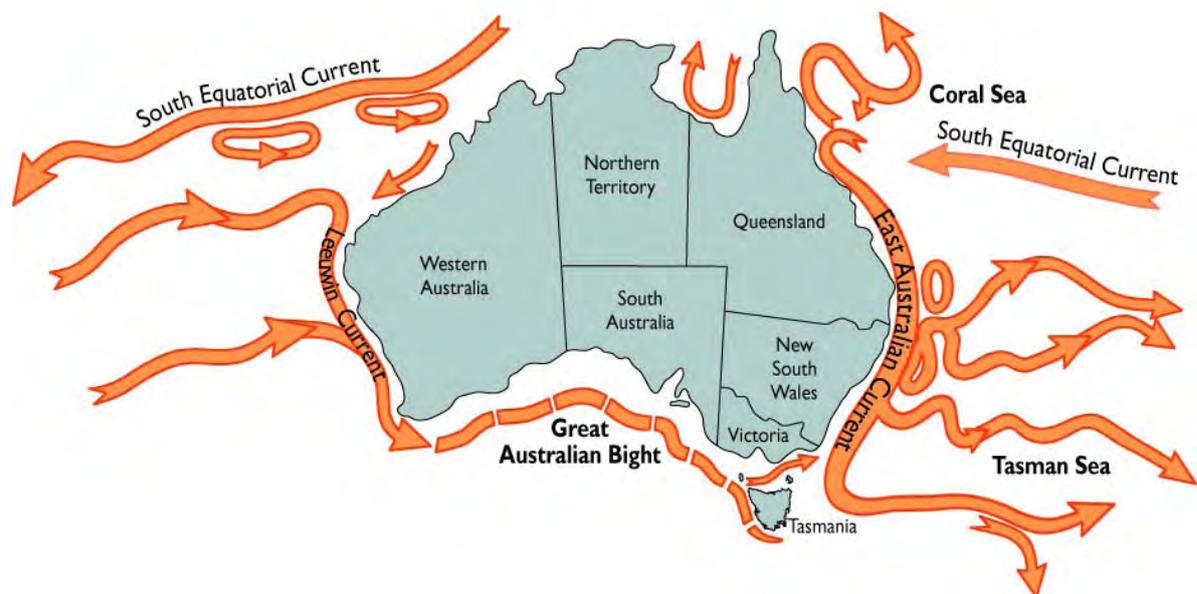
Figure 1.1 Major currents and circulation patterns around Australia. The continent is bounded by the Pacific Ocean to the east, the Indian Ocean to the west, and the Southern Ocean to the south.

Investigating Climate Change Impacts

There is increasing awareness that oceanic processes, for example advection and water temperature, affect biological processes such as recruitment to fish stocks. However, to date there has been little supported and coordinated climate change research on such processes. Considerable progress is being made through research on the role of climate variability (such as El Niño – Southern Oscillation events) in influencing biological processes, which will inform how climate change may impact fish stocks. This approach typically requires time-series of biological and physical data covering more than one cycle of the climate variability pattern. Climate variability usually operates on shorter time-scales, such as annual or decadal, while climate change operates over many decades or longer. The terms "environmental variation" and "climate variability" are used interchangeably in this review: both refer to short-term changes in the environment. "Climate change" is used to refer to long-term environmental changes.

The evidence for climate change impacts on marine fisheries so far, has been largely inferred from studies of climate variability. This is because (i) climate change scenarios for the coastal and pelagic environments have, until recently, lacked the spatial resolution necessary for biological studies, and (ii) most fisheries and their captured species are not amenable to experimental manipulation, and so climate change impacts cannot be readily measured as for some terrestrial or benthic systems, such as coral. Further, Australia suffers from a lack of long-term data for most fisheries, which hinders research into climate impacts, despite more than a century of exploitation in some regions. Fishers were not required to complete fishery logbooks until comparatively recently; the logbooks are the most common data source used to assess resource abundance. Fishery-independent sampling is far less common. Australia's participation in several international programs focused on the climate impacts on fished species may help to overcome the temporal limitation by enabling spatial comparisons between regions. Two such programs are the GLOBEC (Global Ocean Ecosystem Dynamics) initiatives - SPACC (Small Pelagics and Climate Change) and CLIOTOP (Climate Impacts on Top Ocean Predators). This Australian contribution to these international efforts will likely increase in the coming years.

Climate Change Impacts on Marine Fisheries

Climate change can influence biological systems by modifying (Walther et al. 2002):

1. phenology and physiology; for example the timing of spawning, or the tolerance to increased water temperatures.

2. range and distribution (including local or global extinction); for example, the contraction of suitable habitat for salmon farming (Chapter 2).

3. composition and interactions within communities; for example, expansion of the range of the sea urchin *Centrostephanus rodgersii* along Tasmania's east coast has been implicated in the decline of algal communities that support the valuable abalone and rock lobster fisheries (Chapter 4). Climate-facilitated species invasions also impact biological communities.

4. structure and dynamics of communities, including changes in the productivity due to physical changes in the environment such as wind-driven upwelling.

In this review, we discuss the impact of climate change on Australian fisheries and aquaculture considering these four attributes. Attention is paid to the key physical processes relevant to each fishery or aquaculture sector. However, there is as yet insufficient knowledge about impacts of climate changes on regional ocean environments and about physical-biological linkages to enable confident predictions of changes in fisheries productivity. The increasing importance of marine aquaculture makes this industry of particular concern (see Chapter 2). For example, the gross production of the salmon aquaculture industry based in Tasmania was valued at A\$221 million for 2005/06 (ABARE 2007). Atlantic salmon in Tasmania are farmed near the upper thermal limits for optimal growth so the projected warming in this region may have considerable consequences for the industry (although it may be possible to adapt stocks through selective breeding or mitigate by moving cages offshore to deeper, cooler waters).

Faced with the very limited published research on how climate change may affect Australian fisheries, the first step is to increase understanding about current relationships between climate and marine biota. This review, undertaken for the

Department of Climate Change, summarises the latest information on the link between climate and marine biota to identify possible climate change impacts and to suggest strategies for mitigating or adapting to these potential impacts. Information from the primary literature, external reports and internal research work is included.

Climate Projections for Australia

A range of coupled climate models have been used to investigate the response of the physical ocean-atmosphere system to increased emissions of greenhouse gases and aerosols (e.g. Cubasch et al. 2001). This section examines those aspects of climate model simulations most relevant to assessing the impact of climate change on marine fisheries and aquaculture. Because Australia's marine environment is diverse, with large physical differences in coastal and shelf environments, there are many specialised environments. With a limited ability at present to project future local impacts of climate change, we focus our summary on the larger scale and general trends being projected by climate models.

The key variables expected to drive climate change impacts on fisheries and aquaculture are changes in temperature, ocean currents, winds, nutrient supply, rainfall, ocean chemistry and extreme weather conditions. It is very likely that changes in any of these would also significantly change the marine ecosystems (Denman et al. 1996, Cox et al. 2000, Bopp et al. 2001, Boyd & Doney 2002, Sarmiento et al. 2004), and consequently the distribution, growth, recruitment, and catch of exploited marine species, their prey and predators.

To give an indication of how the Australian marine environment may change, we use climate change projections from the CSIRO Mk 3.5 climate model (hereafter called "the model") (Gordon et al. 2002). Although there are subtle differences between the CSIRO models and other international models, many of the general trends in these fields are similar and we focus on these trends rather than the absolute magnitude of the predicted changes. Output from the model of the future key environmental variables for Australia using greenhouse gas emissions scenario IS92a, often referred to as 'business as usual', is used in this report (Table 1.1). To provide a setting for the impacts of climate change on fisheries we focus on projections of climate change for the 2030 decade, a period chosen because the temporal scale of interest to many fisheries and aquaculture operators and managers is the next few decades. However, projections for the 2070 decade are also discussed where predictions are more certain.

There is considerable uncertainty regarding climate model predictions, in both time and space. Uncertainty results from model dynamics and resolution, and because the future is not completely known: future changes in greenhouse gases cannot be predicted. Over shorter time periods, climate variability dominates and predictions from models are more uncertain than for longer time scales. At regional scales (100s of kilometres), projections are also uncertain and model development to allow regional downscaling is required in the coming years. Despite this uncertainty, there is agreement between climate scientists about large scale climate features, and we can proceed with caution in exploring future impacts on fisheries and aquaculture. Observational data available for the period since 1990 raises concerns for the speed at which greenhouse gases are impacting the climate system. In particular, sea level may be responding more quickly to climate change than global climate models indicate (Rahmstorf et al. 2007). Therefore, future projections used in this review may be considered as conservative estimates of future climate, and both positive and negative impacts may be of greater magnitude.

Table 1.1 Observed and projected changes in physical and chemical characteristics of Australia's marine realm including the Southern Ocean. The categories match the sub-sections used in each fisheries and aquaculture chapter. The projections are derived from the CSIRO Mk 3.5, under greenhouse gas emissions scenario IS92a, which is a mid-range scenario. SST = sea surface temperature, MLD = mixed layer depth. Observations of change come from a variety of sources summarised in the text.

Physical variables	Observed changes	Projected changes 2030's	2070's
Temperature and solar radiation	SST: Warming recorded Maria Island, Tasmania of approximately 1.5°C since 1950s	SST: Warming of 1-2°C around Australia with the greatest warming off SE Australia (2°C). Solar Radiation: There will generally be increases in incident solar radiation	SST: Warming of 2-3°C around Australia with the greatest warming off SE Australia (3°C). At a depth of 500 m warming of 0.5-1°C. Solar Radiation: Increase in incident solar radiation between 2 and 7 units W m^{-2}
Winds, ocean currents, MLD & ocean stratification	Evidence for changes in currents for the east coast of Australia, few studies on winds, MLD and stratification.	Winds: An increase of 0-0.5 ms^{-1} in surface winds Currents: Increased strength of the East Australia Current	Winds: An increase of 0-1 ms^{-1} in surface winds Currents: A general decline in the strength of surface currents of between 0-1.2 ms^{-1} MLD/Stratification: Almost all areas of Australia will have greater stratification and a shallowing of the mixed layer by about 1 m, reducing nutrient inputs from deep waters
Precipitation, extreme events, and terrestrial runoff	Precipitation Long-term declines in some regions, such as south-east Queensland and south-west Western Australia Storms Increases in intense events noted for recent years	Precipitation Average annual decrease of 0 to 5% over most of Australia. Storms Frequency of intense storms expected to increase	Precipitation Continued decrease over most of Australia. Storms Frequency of intense storms expected to increase
Sea level (not including the rise due to ice sheet melting)	20th century rate of sea level rise of 1.7 ± 0.3 mm yr^{-1}	A rise of 0.3-0.5 m is expected around Australia	A rise of 0.6 to 0.74 m, with greater increase on the east compared with west coast
Acidification (pH)	The pH of surface oceans has dropped by 0.1 units since the industrial revolution	A decline in pH by ~0.1 units	A decline in pH by 0.2-0.3 units
Sea Ice	No significant change in Antarctica over the period 1979-2000, in either observations or model.	Sea ice cover predicted to decrease by 10%	Sea ice cover predicted to decrease in winter (25%), and disappear completely in summer (IPCC 4th assessment WG 1 Report)

Temperature and solar radiation

By the 2030s, waters around Australia will likely warm by 1-2°C (Figure 1.2) and 2-3ºC by the 2070s (Table 1.1). The model projects the greatest warming off south-east Australia (2°C by 2030s), which occurs in association with further southward penetration of the East Australian Current (EAC; Figure 1.4). This is a robust feature of all IPCC climate models with only the magnitude of change differing among models. The strengthening and increased flow of the EAC is driven by large-scale changes in the winds in the southern hemisphere. Evidence of a southward shift in winds over the last several decades is documented in the NCEP reanalysis (Thompson & Solomon 2002).
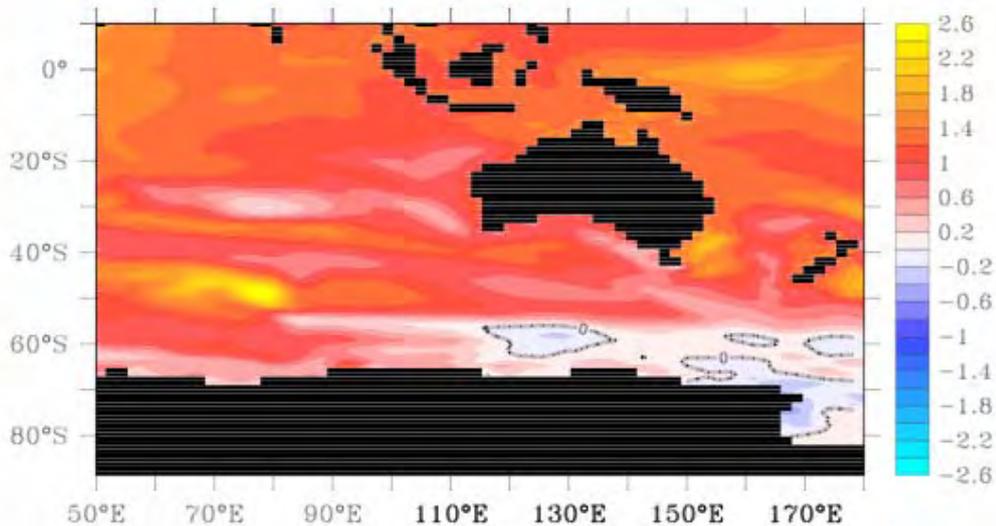
Figure 1.2 The projected annual mean change in sea-surface temperature (°C) by 2030s.

The few long-term water temperature monitoring stations that exist around Australia show recent warming in coastal and offshore marine waters. Trend analysis of a 60-year record of temperature at the surface and at 50 m depth, recorded on the continental shelf at Maria Island on Tasmania's east coast (Lyne, unpublished analyses; Figure 1.3), shows that water temperatures have increased in all months except July at rates of 0.6°C to 3°C per century. The larger increases occurred over the transition months of May and November, when the expansion and contraction of East Australian Current waters past Tasmania is evidenced. On average, temperatures have risen by about 1.5°C per century. This observed warming is comparable to the annual mean change projected by the model.
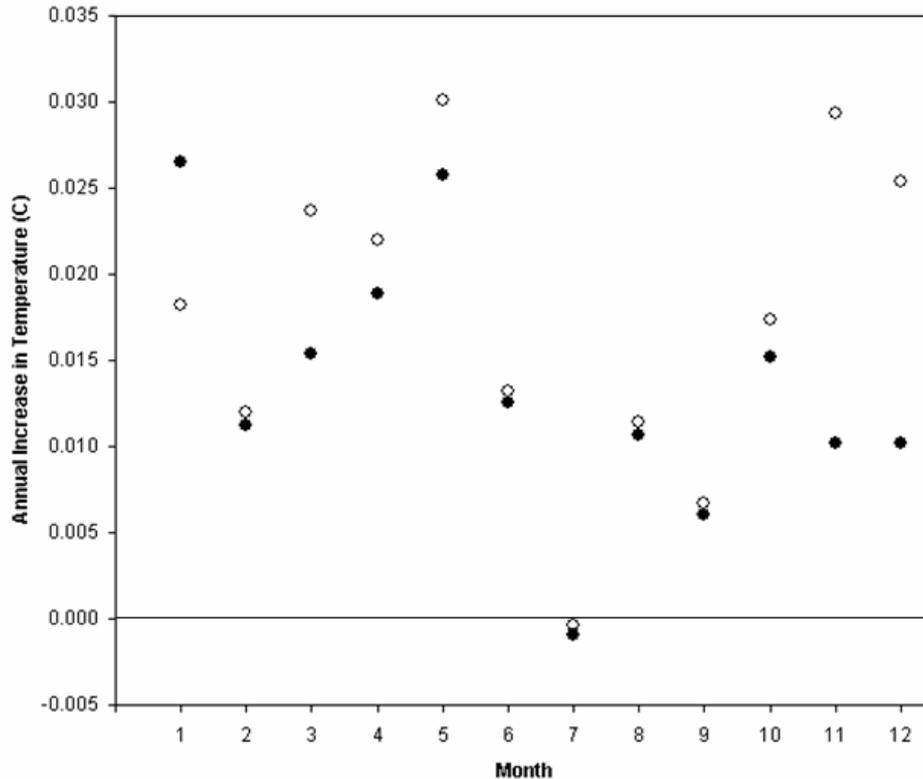
Figure 1.3 Variation by month in the slope of the long-term warming trend measured at Maria Island off the east coast of Tasmania on the continental shelf in degrees per year (1943-2003). The trends at the surface (open circles) and at 50 m (filled circles) depth are shown. The data are averaged for the 60 year period ending 2004. Data below the horizontal line indicate months in which the temperature has decreased over the period considered; data above the line indicates months in which temperature has increased over the period. The y-axis is the annual increase in temperature over the 60 year period considered.

Winds, currents, MLD & stratification

Under the global warming scenario used in the model, the surface current on the east coast of Australia shows a systematic change: the East Australian Current strengthens and there is increased southward transport as far south as Tasmania (Figure 1.4), related to the southward migration of the high westerly wind belt (Figure 1.5). On the west coast, however, there is no obvious strengthening of the Leeuwin Current, which is due in part to model resolution. Along the southern coast (Great Australian Bight), the region experiences more westward transport. On the north-west and north-east coasts there is an increase in the northward flow.

In general, Australian coastal areas are downwelling regions due to prevailing winds and the density structure of the upper ocean (Figure 1.6). In the oligotrophic regions of Australia, the principal mechanism of nutrient supply to the upper ocean is convective mixing in winter due to cooling of the surface waters. When the surface of the ocean warms, as it is predicted to do with climate change, the ocean would become more stable because the surface waters would be less dense and sink less readily; mixing would therefore require more energy. The supply of nutrients to the upper ocean would be reduced, which is likely to result in declining productivity. In the few regions where upwelling increases in strength (e.g. eastern Great Australian

Bight), an increased nutrient supply to the surface could occur if the upwelled water comes from below the thermocline. The potential changes in wind-driven upwelling, however, are not well predicted by the model, and require further investigation.
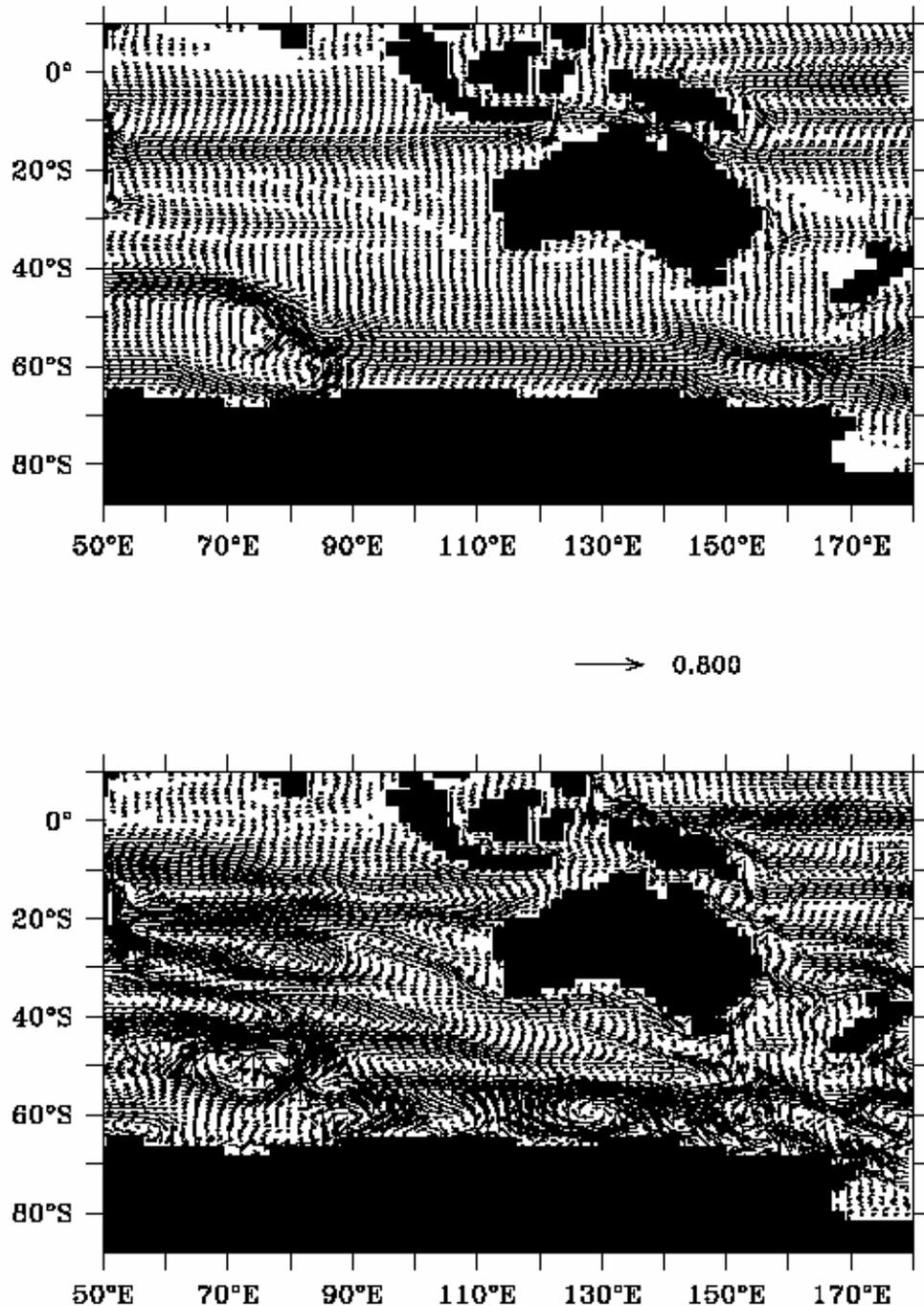
Figure 1.4 Upper ocean annual mean currents from the model's control run (upper panel) and change from the control run for 2030s (lower panel). The direction and strength of the currents are indicated by the arrows at each grid point in the panels. The scale arrow between the panels denotes the scale for the plot in ms^{-1} in the upper panel and 0.1 m^{s-1} in the lower panel.
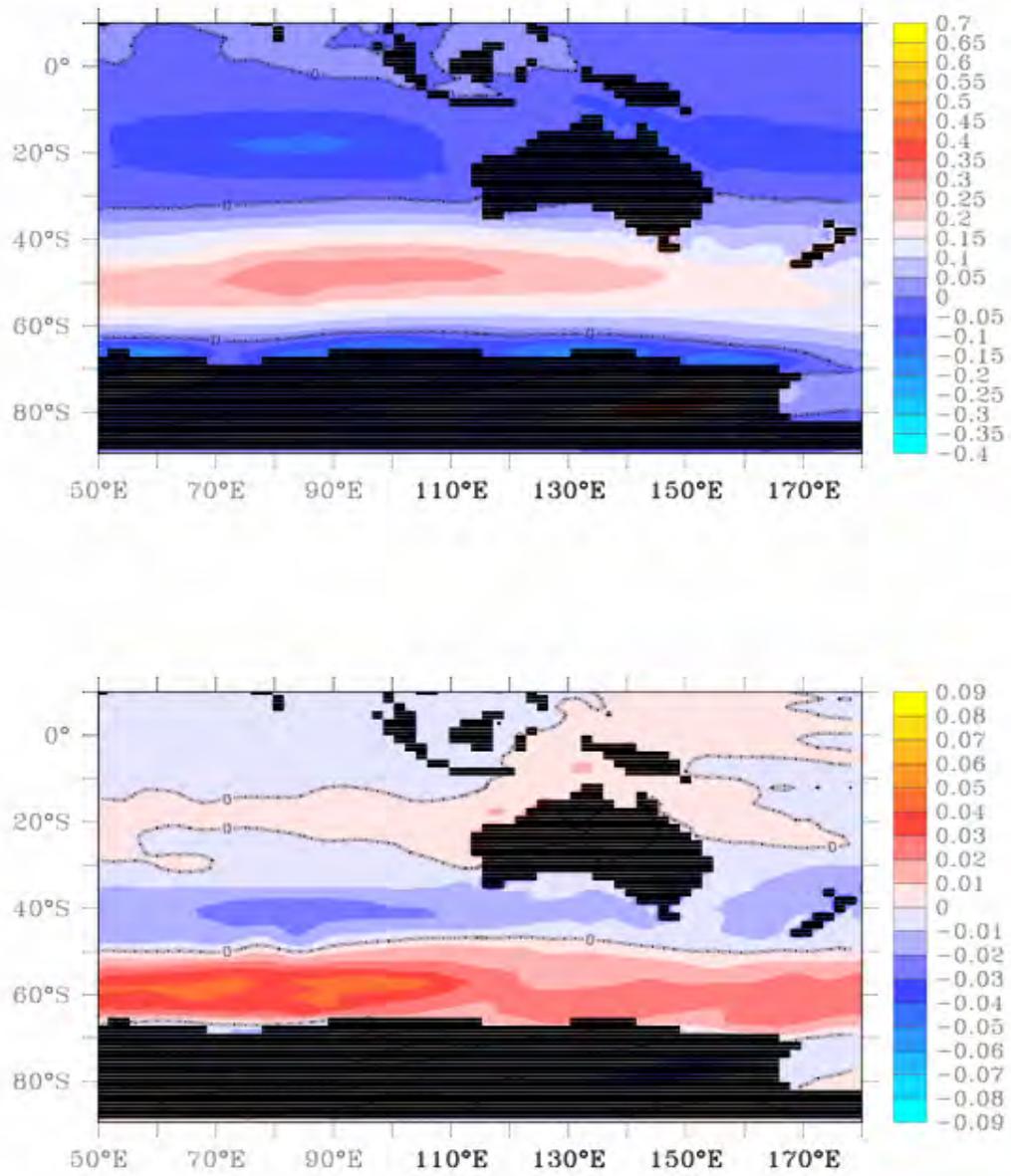
Figure 1.5 The annual mean zonal surface wind stress from the model control run (upper panel) and change from the control run for 2030s (lower panel) in Pa.
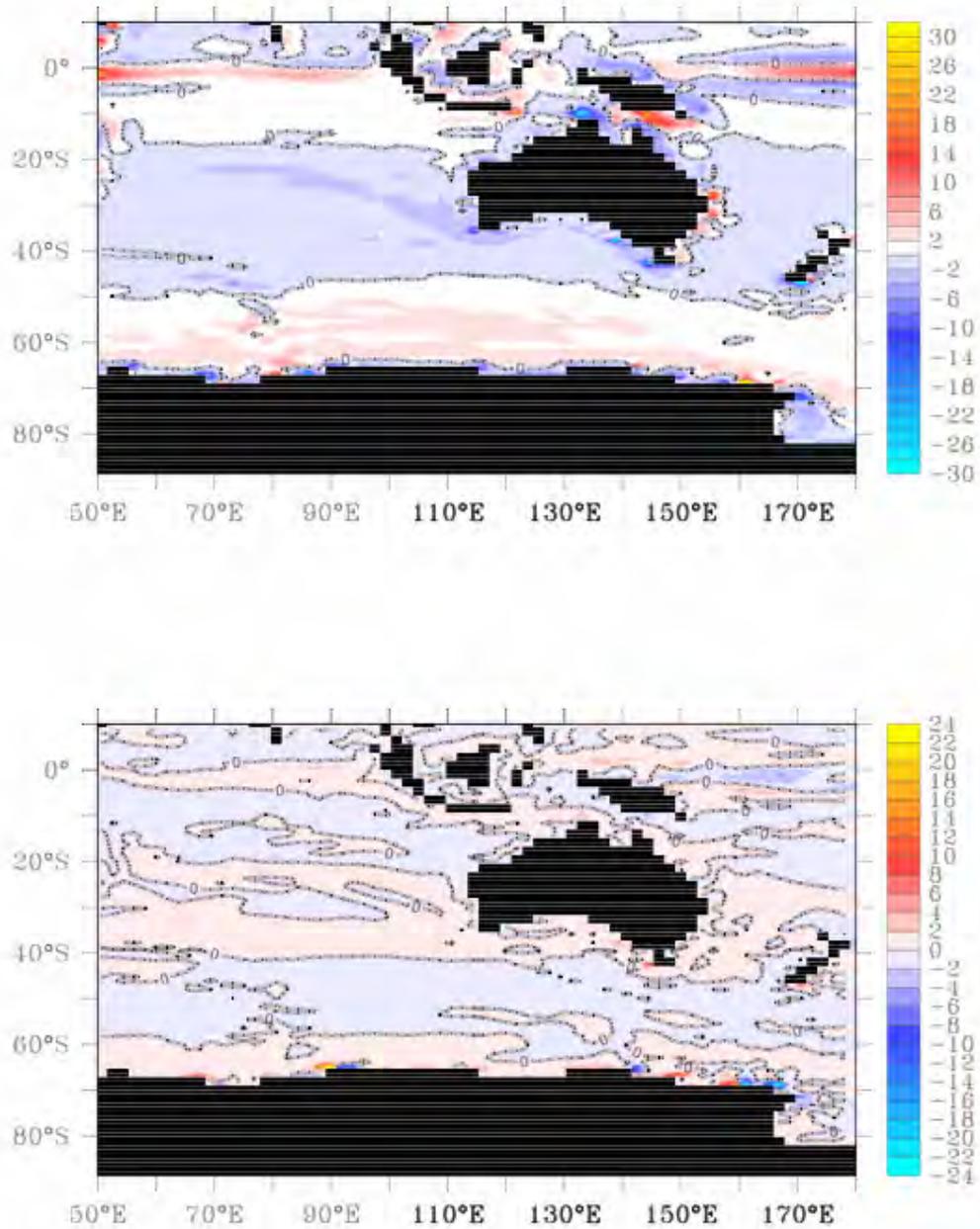
Figure 1.6 Vertical water velocities at 50 m depth for the control run (upper panel) and for 2030s (lower panel) in ms^{-1}. A positive number denotes upwelling of water to the surface from 50 m; a negative number indicates downwelling of water.

Precipitation, extreme events, and terrestrial runoff

Changes in rainfall with climate change would alter the amount of river run-off flowing into the coastal environment. Under the CSIRO Mk3 model, the projected annual mean changes in rainfall from the year 2000 shows a reduction in rainfall throughout Australia, and especially in western Australia (Figure 1.7). The projected reductions in rainfall in southern Australia are common to almost all international climate model simulations, with the rainfall reductions concentrated in the late winter–spring period. However, the severity of the rainfall reductions in the south is model-dependent, with the CSIRO model towards the lower end of the projected changes. In northern Australia, the projected changes in rainfall are much less clear: some models project an increase in rainfall while others project a decrease.
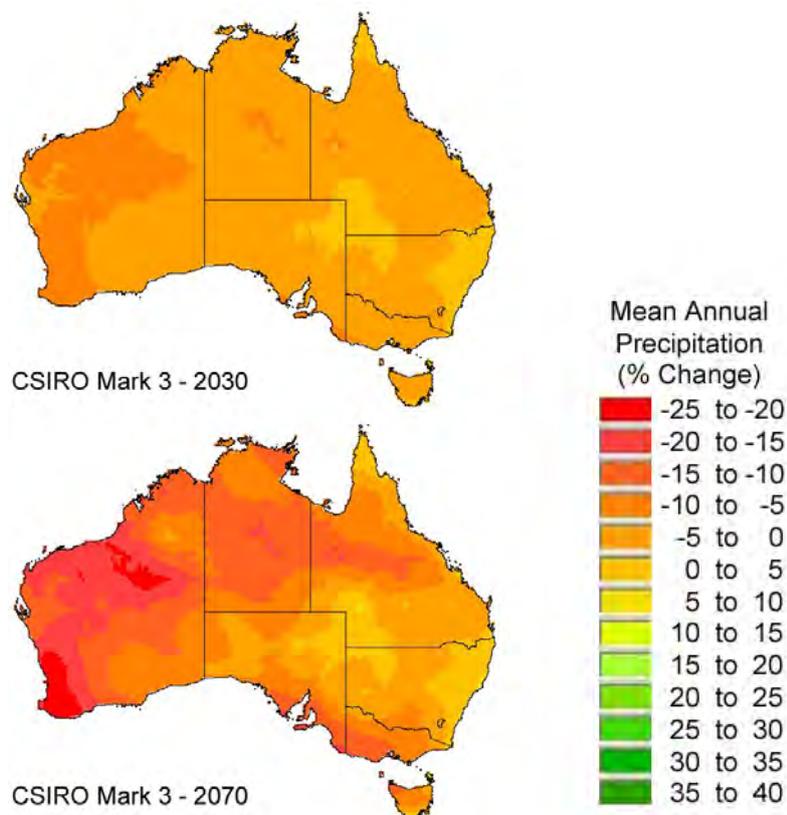
Figure 1.7 Change in the mean annual rainfall in 2030s and 2070s predicted by the model. The percentage change in annual mean rainfall is compared to the year 2000.

An increase in extreme events, such as cyclones, storms and floods, is also a potential consequence of climate change (e.g. Graham & Diaz 2001, Allan et al. 2003). For coastal and offshore aquaculture, stronger and more frequent storm conditions could result in increased physical damage and stock losses, both costly to operations. Many coastal processes, such as sediment transport, take place mostly during high-energy events (storms). An increase in storm activity might therefore, initiate changes in bottom conditions, increase erosion or affect facilities not directly exposed to increased winds and waves (e.g. mass mortalities in tuna cages in Port Lincoln caused by increases in turbidity; see Preston et al. 1997). Extreme flooding can result in mass

mortalities of farmed marine species (e.g. low-salinity killed farmed prawns during a one-in-50 years flood event at Clarence River, NSW, in 1998). Damage to fisheries infrastructure, including ports and vessels, may also occur during storm events. The potential economic impact of these extreme events is, however, unknown. Based on a range of climate models it is highly likely that the frequency of extreme events, such as heat waves and heavy precipitation events will increase in the future. It is also likely that the intensity of tropical cyclones will increase, although it is uncertain if frequency will alter. Coastal systems may be particularly vulnerable to changes in the frequency of extreme events, and increased partnership between climate modellers, biologists and socio-economists, is required to develop plausible scenarios for climate change and impacts.

Sea level rise

A rise in sea level would flood existing low-lying coastal environments and change the marine habitat of coastal and estuarine environments. With climate change, the climate model projects a doubling in the rate of sea level rise for the present century from the observed 1.44 mm/year estimated for the 20th century. Although sea level rise will vary from place to place, by the end of the 21st century the projected sea level increase will be in the order of 28 to 34 cm above the 1990 value. These estimates are conservative because the IPCC models have not considered the contribution from collapsing ice sheets, which could increase estimates by up to 5 m (Oppenheimer et al. 2007).

Acidification (CO_2 and pH)

In addition to the changes in the physical circulation described above, oceanic carbon dioxide (CO_2) will increase as the anthropogenic CO_2 is absorbed by the oceans around Australia. This increase in absorption will lead to oceans becoming more acidic, and consequently animals and plants would use more energy to build and maintain calcified structures. Rising CO_2 levels are projected to impact the calcification rate of coral and other calcifying organisms in the ocean (e.g. Hughes et al. 2003, Baker et al. 2004). Although there may not be a direct impact on the abundance and distribution of exploited marine organisms, the potential impacts of such a change on marine ecosystems could be catastrophic (Raven et al. 2005).

Sea-ice

In the Antarctic region, the dominant change in the ocean environment is the general decline in winter sea-ice, particularly along the Antarctic coast west of Australia. In this region there is a dramatic reduction in the extent of sea-ice. This reduction is coupled with general warming and reduced salinity, which helps stabilise the water column and reduce the ventilation of the deep water. In the Antarctic divergence region, the large-scale ocean circulation experiences a reduction in upwelling, which reduces the supply of nutrients to the Southern Ocean. Additional sea ice impacts are discussed in the chapter on Sub-Antarctic Fisheries (Chapter 7).

Review Structure – Fishery Regions

This review has been organised by considering Australian fisheries in a number of geographic regions that reflect broad management areas (Figure 1.8). Aquaculture industries around Australia are covered in a single section. Coastal fisheries are divided into northern, south-east, and western sections; one section covers the pelagic fisheries around Australia; and one section the sub-Antarctic fisheries. Within each section, the known relationship or response to the physical environment for species in the fisheries is documented. Each section ends with a summary of key points. This review is not comprehensive with regard to all Australian fisheries and aquaculture sectors. By reading the sections appropriate to a geographic area, stakeholders of fisheries that are not specifically discussed will gain insight into the physical changes that will likely occur in the region.
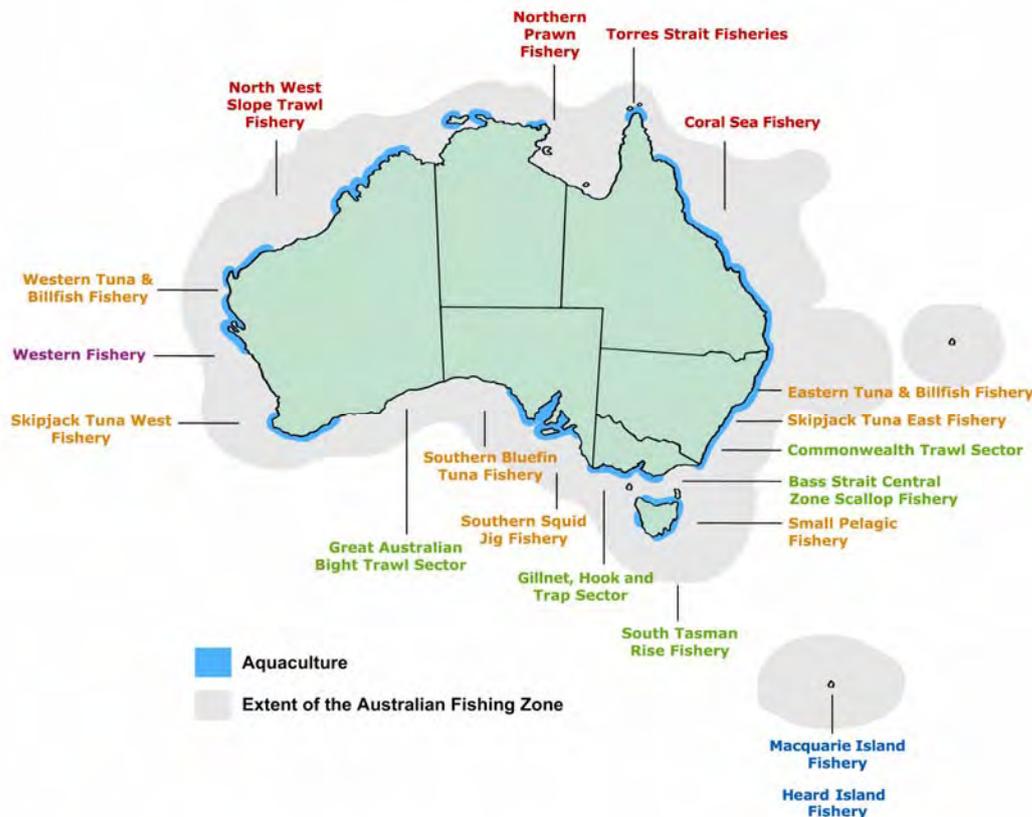
Figure 1.8 Fisheries covered in this review. The colours correspond to the chapters in which the fisheries are covered. Aqua: Chapter 2 Aquaculture, Red: Chapter 3 Northern Fisheries, Green: Chapter 4 South-east Demersal Fisheries, Purple: Chapter 5 Western Fisheries, Orange: Chapter 6 Pelagic Fisheries, Blue: Chapter 7 Sub-Antarctic Fisheries. Figure modified from http://www.afma.gov.au.

Synthesis of Review Findings

Climate change has been documented in many of the regions around Australia. It is apparent from studies in Australia and elsewhere in the world that this change will impact the biological, economic and social aspects of fisheries, as evidenced from the historical and present response to climate variability in each of the sections of this report. Despite a lack of empirical evidence for climate relationships in many Australian fisheries and regions, we can make some preliminary statements. It seems likely that climate impacts will affect the social and economic aspects through

biological changes, such as changes in species distribution, which may lead to increases or decreases in costs. Flow-on effects to regional populations where fisheries are important economic drivers may be significant.

This review of fisheries and aquaculture species has shown that, of the four biological attribute areas likely to be impacted by climate change (outlined in the Introduction), most of the known relationships allow impact assessments in only one area: changes in the distribution and abundance of exploited marine species. Changes in the remaining three areas: phenology and physiology, community composition and interactions, and community structure and dynamics (including productivity), are much less certain. There are indications that significant changes will occur in these three areas, but prediction remains a challenge.

In future, additional biological information must be collected to give insight into the impacts of climate change on fisheries and aquaculture. Spatial and temporal information on a range of species, including those currently harvested, trophically-linked species, and others that are ecosystem indicators, is necessary to provide both baseline information and to track climate impacts. Despite a shortage of suitable time-series data on the abundance and distribution of many exploited species, retrospective analyses will continue to play a crucial role. Understanding historical physical-biological relationships at finer scales is becoming possible: ocean models can now provide previously missing or unattainable environmental data, and the research partnership between climate modellers and fisheries and aquaculture scientists must be fostered as these models are developed. This will ensure that relevant biological information, at desirable spatial and temporal scales, will be available from the climate models. Scenario modelling and impact analysis will be increasingly important in future to enable managers and scientists alike to understand the impacts and develop options.

Suggested Future Research and Data Gaps

From the information presented here, immediate progress and maximum returns may be achieved by focused studies in the following areas not currently receiving attention in Australia (other regions, such as the northern prawn fishery and pelagic fisheries are currently being examined e.g. CSIRO Wealth from Oceans Flagship):

- Investigation of climate impacts on south-east demersal fisheries. The relatively long biological time-series already in existence and documented range changes suggest this is an area where clear impact will occur. The south-east area is also the region where climate models indicate rapid warming (Tasman Sea warming) and considerable social disruption would occur if key fisheries were affected. It is important to consider the potential for mitigation or adaptation to any anticipated change. Fisheries and the management approach in this region are also undergoing major restructuring and have shown willingness to consider climate information in setting catch levels.

- Investigation of climate impacts on western rock lobster. The recruitment link currently used to estimate future catch is a statistical relationship whose mechanism is not fully understood. If climate change leads to the decoupling of this link, such that the adult biomass is no longer well predicted by larval settlement, then the current management regime may be compromised, and a valuable and high-profile industry impacted. Elucidating the role of climate variability in this fishery would support a sustainable future.

- Investigation of socio-economic impacts of climate on fisheries and aquaculture. A regional focus study, such as on the Eastern Tuna and Billfish Fishery, where environmental variability is a key driver of fishing effort, or on an aquaculture industry such as salmon farming, would allow development of integrated models predicting how the socio-economic impacts of climate change will be felt. This challenging area would require partnerships between biologists, social scientists, economists and ocean modellers.

- Investigation of changes in productivity around Australia. Current ocean forecasts focus on physical changes; the crucial next step is to forecast change at the base of the food chain. For example, changes in upwelling and mixing may impact regional productivity and thus the range and distribution of key species that occur across a variety of fisheries.

- Investigation of the long-term patterns in distribution and abundance of key species. Studies based on paleo-ecology techniques elsewhere in the world (Baumgartner et al.1992, Finney et al. 2002, Chavez et al. 2003) have shown that fluctuations in fish stocks have been dramatic over periods of thousands of years. Knowledge of past response may inform future change, and such approaches may compensate for the lack of long-term historical data in Australia.

Additional information on the biological relationships with climate variability will enable assessments of future impacts to be made with greater confidence, and management responses justified to sometimes reluctant stakeholders. At this time, there is only a single Australian fishery (Eastern Tuna and Billfish Fishery, see Pelagic Fisheries section) that actively uses climate information in management to minimise interaction with a potential bycatch species (southern bluefin tuna). Australian fisheries and aquaculture management policies, and scientific assessment approaches, do not currently incorporate the effects of climate variability and climate change in setting harvest levels or development strategies. As management and fishing practices move more towards ecological best practices, climate variability impacts on stocks must be considered as a key driver of ecological processes.

Socio-economic Implications

Holistic and adaptive risk management strategies are required for long-term survival of fisheries and aquaculture businesses. The threats from non-climate anthropogenic impacts, in particular over-exploitation, are also significant in fisheries (Kappel 2005). These confounding factors both mask climate effects and threaten sustainability on a time scale that seems more relevant to many policy makers and stakeholders. Ignoring the potential climate impact is unwise, however, and above all, a credible and accurate understanding of the past climate-biology relationships and future climate scenarios is needed to guide informed decision making by operators and managers of marine resources.

Overall, participants in some wild fisheries will see increased opportunity where tropical species move southward, while for southern fisheries, reconciling non-climate threats with increasing temperature will require proactive management.

Climate change impacts on biota may affect fisheries management strategies in several ways. For example, the Commonwealth harvest strategy policy involves setting benchmarks to define overfishing, including biomass limit reference points

(Rayns 2007). These reference points may need to change as species productivity or distribution change, with significant impacts on quotas and effort levels. The guidelines to the policy recognise that account should be taken of changing benchmarks. A difficulty will be in detecting the effects and determining the changes, as each of the fishery sections illustrates. Another management issue is that most fisheries are defined by jurisdictional boundaries that determine access and property rights. As species distributions change, fishers' access to stocks in one region may diminish, while fishers in the new region may not have access rights. Management policies can differ between regions: movement of stocks to areas without adequate management may lead to resource conflict (Miller 2007, Stenevik & Sundby 2007).

Finally, this review has focused on the known ecological relationships with climate variability and thus predicted change. While future work must continue to develop an understanding of the ecological response of exploited marine systems to climate change, one additional area deserves greater attention. Coupling of ecological understanding must be made with socio-economic models to further develop an understanding of the impacts of climate change on Australian marine resources. Economic impacts are also likely for the recreational fishing sectors, where considerable infrastructure and tourism supports regional economies. This broader focus will provide some economic information to underpin the response to climate impacts on exploited marine species. Additional economic information together with a sound understanding of the ecological mechanisms would enable stakeholders involved in marine fisheries and aquaculture to prioritise amongst possible response options.

Key Points: Climate Change and Fisheries and Aquaculture

- Understanding climate impacts on fisheries
  - Australia lacks baseline information on many fished stocks to assess climate impacts.
  - Studies of climate variability lead to understanding about climate change impacts.
  - Paleo-ecology studies can shed light on past responses to climate fluctuation.
- Fisheries will be impacted differently according to the physical changes in the regional environment, for example:
  - South-east fisheries are most likely to be affected by changes in water temperature.
  - Northern fisheries are most likely to be affected by changes in precipitation.
  - Western fisheries are most likely to be affected by changes in the Leeuwin Current.
- Socio-economic impacts
  - Aquaculture industries have considerable adaptation potential via selective breeding, regulating the environment, and new species opportunities.
  - Wild fisheries will see increased opportunity where tropical species move southward, while for southern fisheries, reconciling non-climate threats with increasing temperature will require proactive management.
  - Management structures and policies that account for climate change will allow most flexibility in adapting to future patterns.

2. Aquaculture
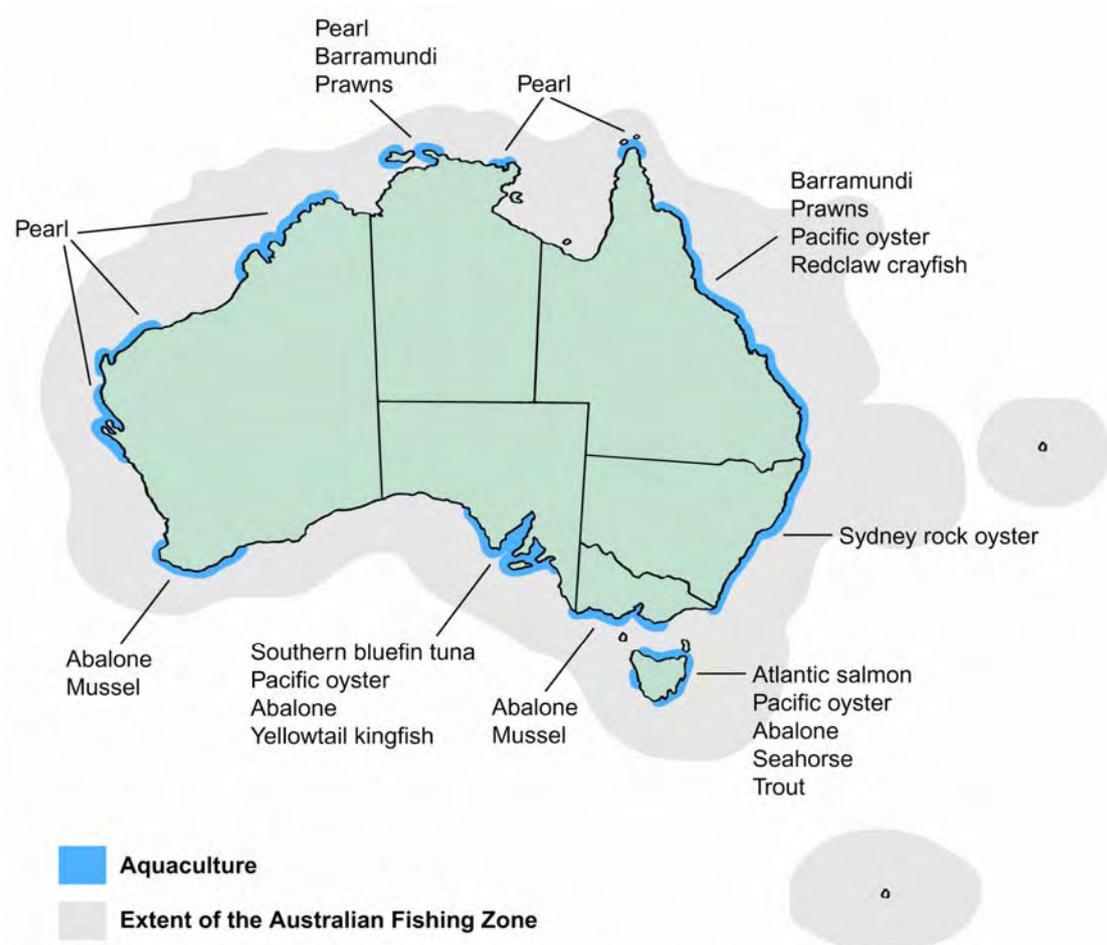
Figure 2.1 Aquaculture industry. Figure modified from http://www.afma.gov.au.

Overview

Aquaculture currently accounts for almost 50 percent of the world's food fish and has the potential to meet the estimated demand for the additional 40 million tonnes of aquatic food that will be required by 2030 to maintain the current per capita consumption (FAO 2006).

Australia's aquaculture sector (Figure 2.1) currently comprises a minor component of global aquaculture value (ABARE 2007), but is an increasingly important component of Australian fisheries production, contributing 35% of the total value in 2005-06 (ABARE 2007). In 2005-06, the value of Australian aquaculture was A$748 million, representing an increase of 18% from 2004-05 driven mainly by a rise in the value of finfish aquaculture (ABARE 2007). In particular, the value of the Tasmanian salmon industry increased by 65% to A$221 million over this period. Salmonids (salmon and trout), southern bluefin tuna, pearl oysters, edible oysters and prawns are the most valuable aquaculture species, accounting for 86% of the industry gross value, but barramundi and abalone aquaculture industries are expanding rapidly (ABARE 2007). Barramundi, prawns and pearl oysters are grown mainly in Australian tropical and sub-tropical waters, while salmon, trout, edible oysters and tuna are cultivated in the

cooler southern waters (Table 2.1). The salmon aquaculture industry is based almost entirely in Tasmania with a very small volume of salmon produced in Victoria and South Australia.

Table 2.1 Aquaculture production (A$'000) of most valuable species per state plus Northern Territory, 2005-06 (from ABARE 2007). * production figures not available.

Species	NSW	Vic	Qld	WA	SA	Tasmania	NT
Salmon	0	0	0	0	0	221,013	
Trout	1,742	8,624	0	0	447	0	
Tuna	0	0	0	0	155,795	0	
Barramundi	1,238	0	13,900	0	2,029	0	*
Pearl oysters	0	0	0	122,000	0	0	*
Edible oysters	34,093	0	570	0	32,480	16,720	
Prawns	3,387	0	46,500	0	0	0	*

In common with other food production sectors, climate change is likely to have direct and indirect impacts on all Australian aquaculture production environments. These include freshwater ponds, brackish water and marine ponds, and industries that use rafts, lines or cages in coastal or offshore waters. Given the projected impacts of climate change on freshwater supplies in Australia (Hennessey et al. 2007), freshwater aquaculture industries may be the most vulnerable. Conversely, pond based or open water marine aquaculture sectors could perceivably benefit from climate change and be well placed to respond to the global demand to aquatic food. For most sectors, data are available on inter-annual variations in production, but there have been few analyses of these data in relation to inter-annual variation in climate. The following section summarises the little we know about the potential impacts of climate change on aquaculture in Australia.

Biological Relationships to Environmental Variables

Temperature and solar radiation

The aquaculture species that are farmed in Australia are sensitive to changes in temperature (Pittock 2003): a change of only a few degrees might mean the difference between a successful aquaculture venture and an unsuccessful one. Analysis of intensively managed prawn farm ponds in Queensland demonstrated that variations in pond temperature had pronounced impacts on farm production, with maximal growth rates of tiger prawns (*Penaeus monodon*) during sustained periods of warmer pond water (Jackson & Wang 1998). This suggests that the production efficiency of tropical and sub-tropical species of farmed prawns, such as *P. monodon* and *P. merguiensis*, might be increased by a rise in water temperature. Rising temperatures may not only enhance growth rates at existing sites, but also extend the cultivation area suitable for farming these species further south. On the other hand, an increase in pond water temperature might threaten the viability of farming cooler-water species, such as the penaeid *P. japonicus*, whose production is restricted to a relatively narrow range of latitudes compared to the sub-tropical species (Preston et al. 2001a). Increased temperatures will affect pond evaporation rates and the resultant increases in pond

salinity could adversely affect less salt-tolerant species (see precipitation section below). However, Australia does have salt-tolerant prawn species, including *Penaeus esculentus* and *P. indicus*, which could be farmed in high salinity ponds.

Penaeus monodon

Image credit: CSIRO

Rising temperatures are of great concern for Tasmania's valuable Atlantic salmon (*Salmo salar*) aquaculture industry. The stocks of these salmon came from Canada and are farmed near the upper limits of their optimal growing temperature in south-eastern Australia. At high and low temperatures productivity is depressed. The projected warming of 2-3°C by the 2070s (under a mid-range greenhouse gas emission scenario) may render salmon farming unviable at current production sites in Tasmania. One potential response to the projected warming would be to move the Tasmanian salmon grow-out cages offshore to deeper, cooler waters. There is increasing global interest in offshore aquaculture for a number of reasons, including the need to avoid adverse impacts on fish health and quality from pollutants discharged into coastal waters (Ryan 2004). Ameliorating the impacts of climate change, particularly for species at the limits to their thermal tolerance, may provide additional incentive to develop offshore aquaculture technology.

The occurrence of temperature-induced disease outbreaks is also expected to increase as global temperatures rise (Harvell et al. 2002). For example, large-scale mortalities of wild abalone in along the south Australian coastline and in California may have been aggravated by warmer temperatures, predisposing the abalone to infection (Goggin & Lester 1995, Vilchis et al. 2005) and raising considerable concerns for the developing abalone aquaculture industry. Since farmed abalone are at the early stages of domestication, a critical strategy for this, and many other aquaculture industries, will be to selectively breed for optimal tolerance to altered temperature regimes. This could also result in increased production efficiency due to faster growth at higher temperatures.

Winds, currents, MLD & stratification

Alteration of currents, winds and mixed layer depth will affect aquaculture through changes in primary productivity, altered distributions of diseases, biofoulers and marine pest species, and increased frequency of harmful algal blooms.

Precipitation, extreme events, and terrestrial runoff

The projected decreases in rainfall over much of Australia will impact freshwater aquaculture industries that rely directly on rainfall to supply their dams or ponds or to recharge groundwater supplies. Adequate supplies of freshwater are required to maintain the water quality in these systems. The projected increases in the intensity of storms and cyclones will increase flood risk, which is a threat to stock through overflows or damage to pond or dam walls. Both reduced freshwater supply and flood events are significant threats to pond aquaculture systems in brackish water areas, such as those used for prawn production. Rainfall affects the salinity of brackish water ponds, which can affect farm production significantly. In 1998, a prawn farm on the Clarence River in northern NSW switched from farming *P. monodon*, a brackish water species, to *P. japonicus,* a more valuable species unable to tolerate low salinities. Unusually high rainfall resulted in a rapid drop in salinity to levels that were lethal for *P. japonicus,* causing mass mortality of the farm crop (Preston et al. 2001b).

Changes in suspended sediment and nutrient loads resulting from altered rainfall patterns will affect aquaculture in both brackish water ponds and in open waters. High inorganic sediment loads can reduce or arrest the filtration rates of oysters (Loosanoff & Tommers 1948). Elevated nutrient levels can stimulate algal blooms containing toxins that accumulate in the oysters, posing a threat to public health (Nell 1993). Over the past decade, the Australian prawn-farming industry has significantly reduced the loads of total suspended solids and nutrients discharged from aquaculture ponds, principally by using dedicated sedimentation ponds (Jackson et al. 2003). Any increase in the sediment and nutrient loads in water bodies that supply aquaculture ponds will increase the costs to aquaculture of meeting effluent nutrient and discharge standards.

For coastal and offshore aquaculture, more frequent and intense storms result in increased physical damage and stock losses, both of which are costly to operations. Many coastal processes, such as sediment transport, happen mostly during high-energy events (storms). An increase in storm activity may therefore initiate erosion. These and other effects can impact facilities outside the direct exposure to increased wind and wave activity. For example, in April 1996 Australian tuna farms at Port Lincoln in South Australia suffered losses of up to 75% of total production, which was attributed to asphyxiation of fish by sediments re-suspended during a severe storm (Preston et al. 1997). Any severe flooding event could result in mass mortalities of animals in aquaculture ponds, open-water rafts, and lines or cages in coastal and offshore areas.

Image credit: Tru Blu Prawn Farms

Sea level rise

Sea level rise is of particular concern for coastal communities in low-lying areas. Rising sea levels may be either positive or negative for coastal aquaculture depending on locality. Sea level rise may result in either a gain or a loss of aquaculture area.

Acidification (CO_2 and pH)

Alteration of ocean acidity is known to directly influence metabolic activity of marine animals (Kikkawa et al. 2003, Pörtner et al. 2004), although little is known about the effects of a long-term, gradual lowering of pH. It is expected that the synergistic effects of warmer temperatures and increased ocean acidity will adversely impact growth and reproduction in marine fish and other fauna, although some species may be able to adapt to the change. Experiments have shown that metabolic efficiency, calcification rates and growth rates of molluscs, including the blue mussel *Mytilus edulis* and the Pacific oyster *Crassostrea gigas*, will be impaired (Michaelidis et al. 2005, Berge et al. 2006, Gazeau et al. 2007). A decrease in calcification rate in farmed molluscs may result in substantial economic loss (Gazeau et al. 2007)

Impacts of Climate Change on Aquaculture

Socio-economic impacts

It is expected that climate change will have adverse impacts on the production of species in Australia's cooler southern waters, particularly on the Tasmanian salmon industry. The Tasmanian salmon industry accounts for over 75% of the value of the state's aquaculture production (and 30% total Australian aquaculture production) and employs over 650 people (estimated for 2003-2004, ABARE 2007). The recent above average summer water temperatures in southern Tasmania have increased mortality (Pittock 2003). However, moving the salmon cages offshore to deeper, cooler waters may reduce the impact of warming temperatures.

Of large concern is the potential impact of climate change on the supply of aquaculture-feed ingredients. Feeds used in the culture of carnivorous fishes and crustaceans generally contain high concentrations of protein, much of which is at present obtained through the inclusion of wild-harvest fishmeal. Expansion of aquaculture industries is placing increasing demand on global supplies of wild-harvest fishmeal to provide protein and oil ingredients for aqua-feeds. The potential for adverse impacts of climate change on global fishmeal production is well illustrated by periodic shortages associated with climate fluctuations such as El Niño (Barlow 2002). Irrespective of the impacts of climate change, production of fish meal and fish

oil from the oceans is likely to decline as demand increases. Over the past 20 years, efforts to find cost-effective alternatives have centered on proteins from terrestrial plants, particularly soy bean meal. If, as seems likely, the use of soy bean meal and other terrestrial plant proteins increases, then the impacts of climate change on national and global terrestrial crop plant industries will become increasingly relevant for finfish and crustacean aquaculture.

The impacts of climate change on aquaculture are likely to heighten public awareness of the need to respond to the changes. As many aquaculture ventures are in public waterways, acute impacts - such as the farmed tuna mortalities noted earlier - are likely to be highly visible. This increased awareness could lead to more concerted efforts to rigorously assess and predict the likely impacts of climate change on aquaculture. At the same time, quota reductions in the wild capture fisheries are having major impacts on the economic viability of coastal communities outside the cities; aquaculture is one of the few alternative sources of employment generally available in coastal towns. The interaction of social and economic factors in relation to climate impacts and setting public policy has yet to be played out.

Industry adaptation capability

The aquaculture industry has several options for adaptation to climate change including; selectively breeding for tolerance to altered temperature regimes; the use of alternate species that are pre-adapted to the temperature regimes; relocation of production facilities, including the movement of cage systems to deeper offshore waters; and the development of new industries including microalgae biomass production. The emergence of global interest in the potential for mass cultivation of microalgae as a source of biofuels, feeds, chemicals, pharmaceuticals and nutraceuticals (Benemann 1992, Borowitzka 1997, Spolaore et al. 2006, Chisti 2007) could provide an opportunity for Australia to take advantage of increased solar radiation and elevated temperatures. The development of this new aquaculture sector could be particularly significant if mass cultivation of microalgae proves to be an effective method of post-combustion of CO_2 from Australia's coal fired power stations (Kaddam 1997, de Morais and Costa 2007).

The predicted temperature change in waters around Australia over the coming century is relatively slow compared to the generation times of the Australian aquaculture species that are currently considered amenable to selective breeding; these range from a year or less for prawns (Preston et al. 2004), two years for oysters (Appleyard et al. 2006) to three years for Atlantic salmon (Elliott & Riley 2003) and temperate abalone (Shepherd et al. 1974). Although there appears to be significant potential to adapt these aquaculture species to changes in temperature within appropriate time frames, whether this is possible will depend on the genetic diversity of the breeding population.

Key Points: Aquaculture and Climate Change

<u>Physical</u>

- Sea levels are projected to rise all around Australia, increasing the risk of low-lying coastal inundation.

- A general decrease in rainfall is projected for all of Australia, while the intensities of severe storms and cyclones are expected to increase.

<u>Biological</u>

- Increases in temperature may reduce production efficiency of key cool water farmed species, such as Atlantic salmon, and increase incidences of diseases.

- Alteration of precipitation patterns will alter salinity, nutrients and suspended sediment levels of coastal waters with implications for coastal aquaculture.

- The viable regions for aquaculture will shift, depending on species.

<u>Socio-economic</u>

- The Tasmanian salmon industry contributes a large portion of Australian fisheries production value, so the threat of warming temperatures is of large concern, but may be mitigated by moving cages offshore.

- Industry has capacity to adapt rapidly through selective breeding of broodstock, and switching to species more suited for future conditions.

Image credit: CSIRO

3. Northern Fisheries
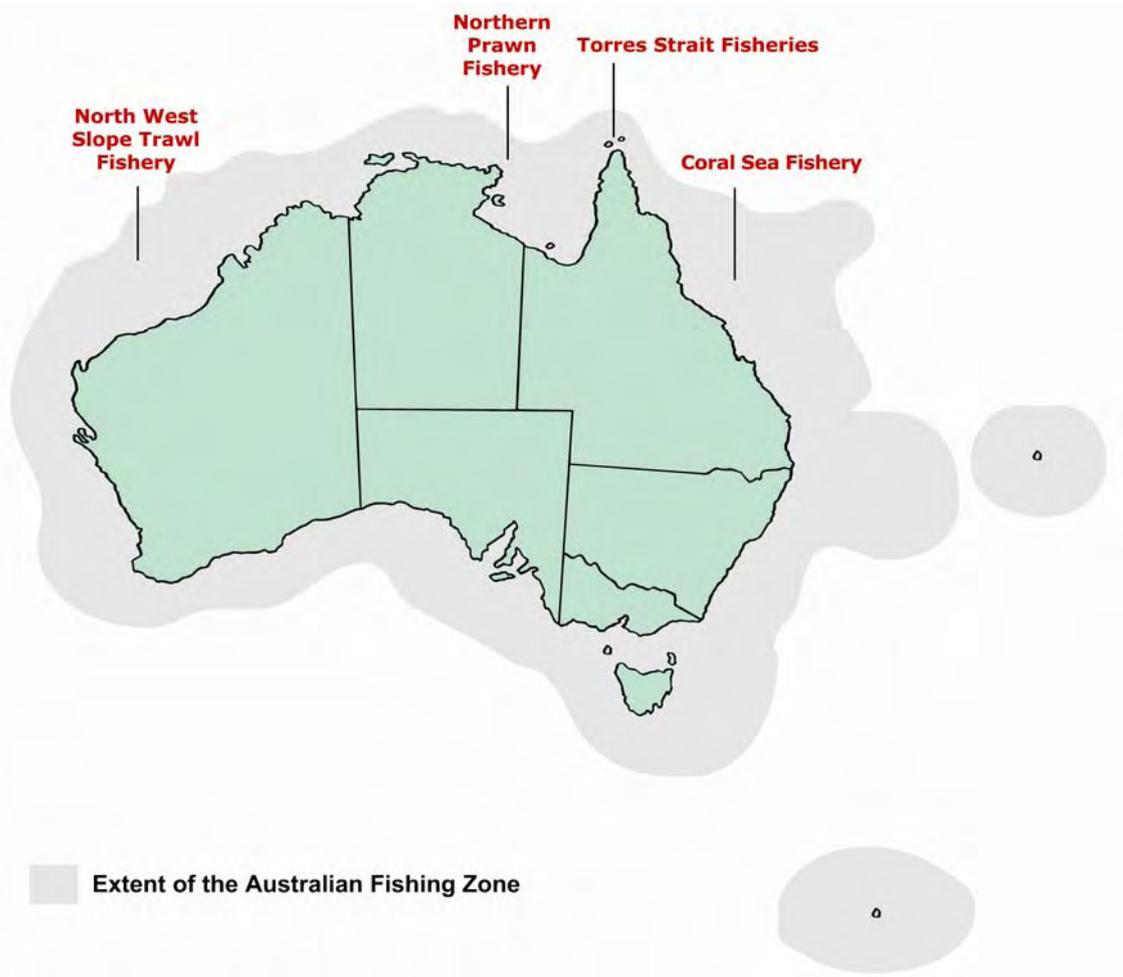
Figure 3.1 Northern fisheries. Figure modified from http://www.afma.gov.au.

Overview

Commercial fisheries of northern Australia (Figure 3.1) target a wide variety of sea life including penaeid prawns and squid, demersal finfish, shark, grey and spanish mackerel, barramundi, threadfin salmon, Torres Strait lobsters, sea cucumbers, trochus shells, coral trout, red throat emperor, various live reef fish, and portunid crabs (see Caton & McLoughlin 2005). A broad range of marine organisms are also taken by traditional (aboriginal) hunting, fishing and gathering, by other artisanal fishing and by recreational fishing (Henry & Lyle 2003). In addition, illegal, unregulated and unreported fishing is growing in northern Australia (DEH 2004).

The Northern Prawn Fishery (NPF) is one of Australia's most valuable commercial fisheries (ABARE 2007), averaging 8,500 tonnes of prawn landings per year over the last decade and an estimated 8 to 21 times that amount of bycatch species (Pender et al. 1992, Brewer et al. 1998, Stobutzki et al. 2000). The average value of the NPF over this period was about A$135 million per year, but declined to A$65 million in 2003-04, largely because of the increase in value of the Australian dollar coupled with strong market competition from imported prawns (ABARE 2007). The value of this fishery has since rebounded slightly to A$73 million in 2004-05 (Stobutzki & McLoughlin 2007).

Because of the diversity of species harvested in northern Australia, it is relevant to consider the ecosystems in which the exploited species occur and the potential climate impacts on biodiversity. The endemicity rate of marine species in northern Australia is about an order of magnitude less than in its temperate zones (~4% and ~40%, respectively) due to differences in geographic isolation (CSIRO 1996). Some authors have suggested that climate changes would therefore have greater impacts on the biodiversity of Australia's temperate zones (e.g. Pittock 2003). Nevertheless, many species not endemic to Australia are in fact confined to the Indo-West Pacific biodiversity hotspot, with Australia becoming a last refuge for some species affected by degrading environments in neighbouring countries. This is worrying given that several lines of evidence indicate Australia's northern (tropical) ecosystems are vulnerable to climate change (e.g. Hill et al. 2002), in addition to the effects of fishing. Thus, the impact of climate change on these ecosystems may have consequences beyond fisheries.

We have limited this chapter to the known or studied relationships between climate variability and northern prawns, with referral to other species taken in northern Australian fisheries. Compared to other Australian fisheries, climate relationships have been well-characterised for northern prawns. Although physical and chemical changes will manifest heterogeneously, one general scenario for the future of northern Australia's estuarine and marine areas is that temperature, rainfall, river flow, turbidity, sea level, and the frequency of severe cyclones will increase, while salinity will decrease (e.g. Hughes 2003 and other citations therein). We surveyed the existing literature to infer vulnerabilities of these prawn species, and thus the NPF, to variations in these environmental characteristics, as well as the potential capability of these species and fisheries to adapt to such changes (physiology and phenology). The likely indirect effects of climate changes as mediated by changes in community structure and function are not discussed as too little is currently known.

Biological Relationships to Environmental Variables

Temperature and solar radiation

It appears that the growth, survival and abundance of various life stages of penaeid species are sensitive to extreme temperatures and to shifts in temperature regimes. Extreme temperature events include the exposure of postlarvae and juveniles to the first few centimetres of incoming flood tide that has absorbed heat from exposed seagrass/mud flats. This first flush of seawater can reach 40°C on mid-summer days (D. Heales, CSIRO Marine and Atmospheric Research, unpublished data). Temperatures have risen faster in northern Australia than the global average (Walther et al. 2002) and they are expected to continue increasing in all seasons, together with an increase in the number of temperature-extreme days (Walsh et al. 2002, Hennessy et al. 2004). Extreme temperatures in the shallow nursery habitat of penaeid prawns may be characteristic effects of climate warming. Extended periods of elevated temperatures in shallow estuarine waters might considerably affect the distribution of prawn nursery habitats, such as seagrasses, because of this extreme solar heating effect. Annual sea surface temperature is projected to rise by 1.6-1.8°C in northern and north-eastern Australia by the 2070s.

Several studies have indicated that high water temperatures can cause decreased growth and survival of the penaeid species that are targeted by northern Australian prawn fisheries. Haywood and Staples (1993) and Staples and Heales (1991) used

field and laboratory studies, respectively, to show that the growth and survival of juvenile banana prawns (*Penaeus merguiensis)* is diminished by high temperatures. O'Brien (1994) found that "combinations of extreme temperatures and salinities were lethal" to juvenile brown tiger prawns (*P. esculentus*). Jackson et al. (2001) found that water above 30˚C contained low densities of tiger prawn (*P. semisulcatus*) larvae in Albatross Bay, Gulf of Carpentaria. Finally, some of Jackson and Burford's (2003) results indicated larval tiger prawns had significantly lower survival at their higher experimental temperatures, and that "high temperatures may cause larval mortality in Albatross Bay". Estuarine temperatures at Weipa in northern Australia are often around or above 30˚C during the hottest part of the year, i.e. close to the level that affects juvenile tiger prawn survival. During the cooler season (winter), Vance et al. (1985) found a positive correlation between higher than usual temperature and catches of *P. merguiensis* in the Gulf of Carpentaria (e.g. 25˚C rather than 20˚C), which suggests that spawning and larval survival of this species might be enhanced by warmer than normal winter temperatures (but hindered by warmer than normal summer temperatures).

Penaeus merguiensis

Image credit: CSIRO

Winds, currents, MLD & stratification

Wind speed and direction influence the currents that advect penaeid prawn larvae and post-larvae from offshore spawning areas to estuarine nursery areas (Rothlisberg et al. 1983, Vance et al. 2003). Changes in normal background wind patterns thus influence patterns of prawn larval recruitment and a reduction of mean zonal winds is predicted. Similarly, dispersal of rock lobster larvae in the Torres Strait is largely influenced by the Coral Sea gyre (Bensley 2007), which is also likely to change during the coming century.

Precipitation, extreme events, and terrestrial runoff

Catches of banana prawns (*Penaeus merguiensis*) are highly positively correlated with rainfall in the south-eastern Gulf of Carpentaria (Vance et al. 1985, CSIRO 1993, Staples et al. 1995, Loneragan & Bunn 1999). However, the positive relationships between commercial catches of *P. merguiensis* and rainfall / freshwater flow appear weaker in other locations in the region (e.g. PNG - Evans et al. 1997; Weipa - Vance et al. 2003), perhaps due to smaller catchment areas and thus a weaker runoff effect in the estuarine nursery habitat, even where average runoff is higher and less variable (Vance et al. 2003).

Loneragan and Bunn (1999) demonstrated statistically significant positive relationships between summer river flows in south-east Queensland's Logan River and annual commercial catches of king prawns (*Penaeus plebejus*), tiger prawns (*Penaeus esculentus*), mud crab (*Scylla serrata*) and flathead (*Platycephalus* spp.). Again, however, the relationship between rainfall and the tiger prawn catch (*Penaeus semisulcatus* and *P. esculentus*) can, in some cases, be weak, ambiguous or negative, rather than positive, such as in settings where there is a lower dependence on estuarine habitats.

Notwithstanding regional and species differences in the relationship with rainfall, penaeid prawn fisheries and other estuarine-dependent fisheries throughout northern Australia appear to be somewhat sensitive to climate-related changes in rainfall and freshwater flow (see Robins et al. 2005 for a longer review). The sensitivity of northern Australia's penaeid prawns to freshwater flows is also well illustrated by the demonstrated relationships between the southern oscillation index, which is strongly associated with regional rainfall patterns, and both banana prawns (positive) and tiger prawns (negative) (Love 1987, Catchpole & Auliciems 1999).

The mechanism(s) behind these rainfall relationships might be higher discharge that flushes juveniles from nursery habitats to the fished region, or changes in salinity in nursery habitats that stimulate the emigration of juveniles (Vance et al. 1985, Staples & Vance 1986, Staples et al. 1995, Vance et al. 1998, Loneragan & Bunn 1999, Vance et al. 2003) or that stimulate primary production (Loneragan & Bunn 1999). Conversely, high rainfall and freshwater flow can inhibit the recruitment of penaeid prawn larvae into estuaries (Staples & Vance 1987, Meager et al. 2003, Vance et al. 2003). Nursery habitat functionality (e.g. Vance et al. 1990, Loneragan et al. 1994, Haywood et al. 1995, Loneragan et al. 1998) thus can be modified on a variety of scales by changes in rainfall / freshwater flow. One of many examples is the adverse effects of increased turbidity, associated with increased rainfall/runoff, on the extent of seagrass nursery areas and thus on tiger prawn stocks due to shading effects (see Catchpole & Auliciems 1999, Hall et al. 1999). Conversely, increased turbidity may have a positive effect on banana prawn stocks; this species (*P. merguiensis)* apparently increases turbidity behaviourally by beating its pleopods to increase refugia and thus reduce predation (Dall et al. 1990, p. 376).

Changes in rainfall and freshwater flow patterns would also be likely to change nutrient runoff into Northern Australia's coastal waters, which strongly influences the productivity of these otherwise low-nutrient tropical waters (see Vance et al. 2003). Changes in freshwater flows related to changes in climate patterns might affect northern Australia fisheries in other ways as well. For instance, a loss of synchrony between the timing of life history stages and environmental forces could disrupt reproductive stages of life cycles and community interactions, especially considering that other interacting species will be responding to these environmental changes in different ways.

Rainfall is projected to decrease slightly across parts of northern Australia, although projections for rainfall are highly uncertain, and some areas even show a slight increase. Staunton-Smith et al. (2004) demonstrated significant positive relationships between year classes of barramundi (*Lates calcarifer;* an important commercial and recreational fish of northern Australia) and freshwater flow to the Fitzroy River estuary. Increased flows apparently increase the recruitment and survival of early life stages by increasing nursery habitat accessibility or productivity. Milton et al. (2005)

found a negative relationship between catch rates of young-of-the-year barramundi and the amount of rainfall during the previous monsoon season, implying a secondary trophic effect of the rainfall-enhanced (cannibalistic) cohort of the previous season on the younger fish produced later in the season. Although large cohorts can reduce subsequent production (a density-dependent effect), the results of both studies imply that barramundi are adapted to some optimal level of rainfall/flow.

Field and laboratory studies indicate that observed variations in salinity are not thought to inhibit the growth or survival of larval *P. semisulcatus* in northern Australia (Jackson et al. 2001, Jackson & Burford 2003). Juvenile *P. merguiensis* and *P. esculentus* are tolerant of extremely low salinities (Dall 1981), but low salinity combined with extreme temperatures can be lethal (Staples & Heales 1991, O'Brien 1994). Evidence suggests that low-salinity events, associated with high rainfall, normally provide a cue for emigration of juveniles from estuarine nurseries to deeper water (Staples 1980, Staples & Vance 1986, 1987, CSIRO 1993, Vance et al. 1998, Meager et al. 2003, Vance et al. 2003). Although prawns can normally avoid extreme low-saline zones, large changes in salinity regimes and distributions (e.g. from changes in precipitation patterns) would change the distributions and characteristics of habitats, thus potentially adversely affecting the ontogenetic stages of penaeid prawns.

Extended periods of low-salinity flows in estuaries due to increased rainfall may affect the distribution of nursery habitats, such as seagrass and algal beds. Some seagrass species are not tolerant of low salinity, so increased freshwater flows may cause the loss of upstream estuarine seagrass communities. Haywood et al. (1995) found that beds of the algae *Caulerpa* mostly disappeared with the onset of the wet season and that juvenile tiger prawns were not caught again until the reappearance of the alga in the dry season. Long-term salinity changes would affect the seasonal patterns of these ephemeral habitats, in addition to affecting habitats such as mangroves.

Cyclones are common in northern Australia during the wet monsoon season (the austral summer), but they are somewhat rare at any given locality. Their destructive forces include strong winds, intense rainfall, extreme waves, extreme currents and storm surges (BOM 2004). Where cyclones do encounter coastlines, their effects on seagrass and mangrove habitats can be catastrophic. Rothlisberg et al. (1988) noted that changes in the frequency, magnitudes or distributions of cyclones have the potential to considerably change northern Australia prawn nursery grounds and thus prawn populations. Cyclone Sandy, for example, removed ~20% (183 km^2) of the seagrass beds in the Gulf of Carpentaria (Rothlisberg et al. 1988, Poiner et al. 1989, Kenyon et al. 1999), and this took nearly 10 years to recover (Hill et al. 2002). There was a reduction in the fishery's catch offshore (Poiner et al. 1993) following the loss of these nursery habitats. Studies in Exmouth Gulf, Western Australia, indicate cyclones to be detrimental or beneficial to penaeid prawn stocks depending on timing, magnitude and proximity (Penn & Caputi 1985, 1986). In 1999, when Cyclone Vance, a category 5 cyclone, reduced the cover of seagrass in Exmouth Gulf to less than 2%, the tiger prawn landings declined from about 400 tonnes to less than 100 tonnes, despite the presence of a good spawning stock. When the seagrass recovered, tiger prawn landings increased to their pre-cyclone levels (Loneragan et al. 2004), but seagrass in the Exmouth Gulf recovered much more rapidly (2 to 3 years) than it did in the Gulf of Carpentaria.

Sea level rise

Seagrass beds and mangrove forests are considered critical nursery habitats for many marine species, including commercially-targeted prawns (Vance et al. 1990, Loneragan et al. 1994, Haywood et al. 1995, Sheaves 1998, Blaber 2000), and these shallow water or intertidal habitats are particularly vulnerable to cyclones, sea level rise, and their interactive effects. Depending on sedimentation regimes, these habitats either retreat landwards as sea levels rise or they disappear if inundation is rapid and coastal relief is low (Ellison & Stoddart 1991, Hughes 2003). Catches of tropical commercial species, such as banana prawns, mud crabs and barramundi, have been shown to be related to mangrove abundance and extent (Lee 2004, Loneragan et al. 2005, Manson et al. 2005). Seagrass beds are known to provide nursery habitat for juvenile prawns and fish (Coles et al. 1993, Watson et al. 1993, Haywood et al. 1995, Loneragan et al. 1998). Projected sea level rise is expected to considerably reduce these habitats in the southern Gulf of Carpentaria (Hill et al. 2002), an area critical to much of northern Australia's prawn fisheries.

Acidification (CO_2 and pH)

Changes to dissolved CO_2 levels in the ocean represent a serious threat to calcifying organisms, such as corals, pteropods and coccolithophores (see Poloczanska et al. 2007). The decline in aragonite saturation state is expected to be greatest off northeast Australia. Acidification is expected to increase physiological stress on many marine fauna (Pörtner et al. 2004, Raven et al. 2005). The threat to tropical coral reefs will impact fisheries dependant on them and may reduce the shoreline protection afforded by offshore reefs. Experiments have shown metabolic efficiency and growth rates of molluscs are impaired (Michaelidis et al. 2005, Berge et al. 2006) and larvae of echinoderms are severely deformed (Kurihara et al. 2004) under lowered pH. Crustaceans may be particularly vulnerable to ocean acidification because of their dependence on the availability of calcium and bicarbonate ions for mineralisation of a new exoskeleton after moulting (Raven et al. 2005). This will impact freshwater species to a greater degree than estuarine fauna, which routinely encounter much greater fluctuations in pH and dissolved CO_2 than projected over the next century under climate change. However, the effects of a gradual long-term lowering of pH are unknown. Other effects of increased CO_2 on marine flora and fauna are less well understood but will affect the physiology of many marine species. Growth of mangroves and seagrasses, being of terrestrial origin, may be stimulated by additional CO_2 levels in the atmosphere and ocean respectively (see Poloczanska et al. 2007) and these form essential habitat for prawns and many coastal finfish species.

Impacts of Climate Change on Northern Fisheries

Socio-economic impacts

There is some evidence that the adaptive potential of banana prawns (*P. merguensis*) is low. *P. merguensis* spawn in both spring and autumn in the south-east Gulf of Carpentaria, but it is the smaller spring-spawning group that makes the largest contribution to the adult stock (Staples & Vance 1986), leading Rothlisberg et al. (1983) to comment that a large amount of banana prawn reproductive output appears to be wasted, which is "from an evolutionary point of view apparently untenable". They suggest that Gulf of Carpentaria penaeid species have not yet adapted to their environment; the Gulf is younger than the penaeid species, which have a relatively

slow rate of evolutionary change. Climate-related changes to northern Australian marine and coastal ecosystems might, therefore, have considerable and lasting impacts on existing northern Australian prawn fisheries. However, many of the penaeid species, including *P. merguensis*, are widely distributed in south-east Asia and elsewhere and are exposed to a range of climates and conditions (e.g. single to double monsoon) (IOC 1989). They might therefore be more adaptable than Rothlisberg et al (1983) suggest.

Image credit: CSIRO

Industry adaptation capability

Hill et al. (2002) found that threats associated with climate change accounted for five of the seven 'extreme' or 'high' risk threats to the seabed biota of the Northern Prawn managed area (out of 36 possible threats ranked by nine experts). The other two 'extreme' or 'high' risk threats were the introduction of a serious marine pest (ranked first) and the direct impacts of prawn trawling (ranked fourth). The high ranking of climate-change threats to northern Australia seabed biota contrasts with global rankings of threats to marine species in general (with regards to species extinctions). For example, Kappel (2005) used the *United States Endangered Species Act* and World Conservation Union (IUCN) Red List assessments to rank overexploitation and habitat loss as the greatest threats to the largest number of species, while the threat of climate change was ranked considerably lower (though climate change threats to marine invertebrates were ranked relatively high). The contrast of these two rankings is not surprising given the relative remoteness of the Northern Prawn Fishery, the extremely low levels of coastal and other developments there, and the relatively few marine activities in the north. We also expect that habitat loss, or changes, will be one of the major results of climate change on the targeted species of northern Australia. We suggest that adaptation by the fisheries of northern Australia will occur only through an understanding of the interactions of climate changes with fishery impacts and other anthropogenic impacts.

The Northern Prawn Fishery is moving to ecosystem based management through the Northern Prawn Fishery Management Plan (1995), which implements various fishery effort, target species and bycatch species limits (AFMA). The management framework allows rapid action to reduce ecological impacts. Such holistic approaches to fishery management will also increase industry adaptation in the face of climate change.

Key Points: Northern Fisheries and Climate Change

<u>Physical</u>

- Rainfall is projected to slightly decrease in parts of northern Australia, however other parts show a slight increase in rainfall. The frequency of severe cyclones may increase.

- Sea level is projected to rise around Australia, and will impact low-profile shores such as mangroves, increasing extent in some areas and decreasing mangrove extent in others.

<u>Biological</u>

- Catches of prawns, barramundi and mud crabs are related to summer rainfall and may be adversely impacted through changes in rainfall patterns and abundance.

- Sea level rise may reduce the area of mangroves, which are essential habitat for prawns and estuarine fish, in the Gulf of Carpentaria.

<u>Socio-economic</u>

- The Northern Prawn Fishery is moving to managing the fishery in an ecosystem context, which will also improve adaptability of this fishery to climate change.

- Other fisheries are not yet well prepared for climate impacts.

4. South-east Demersal Fisheries
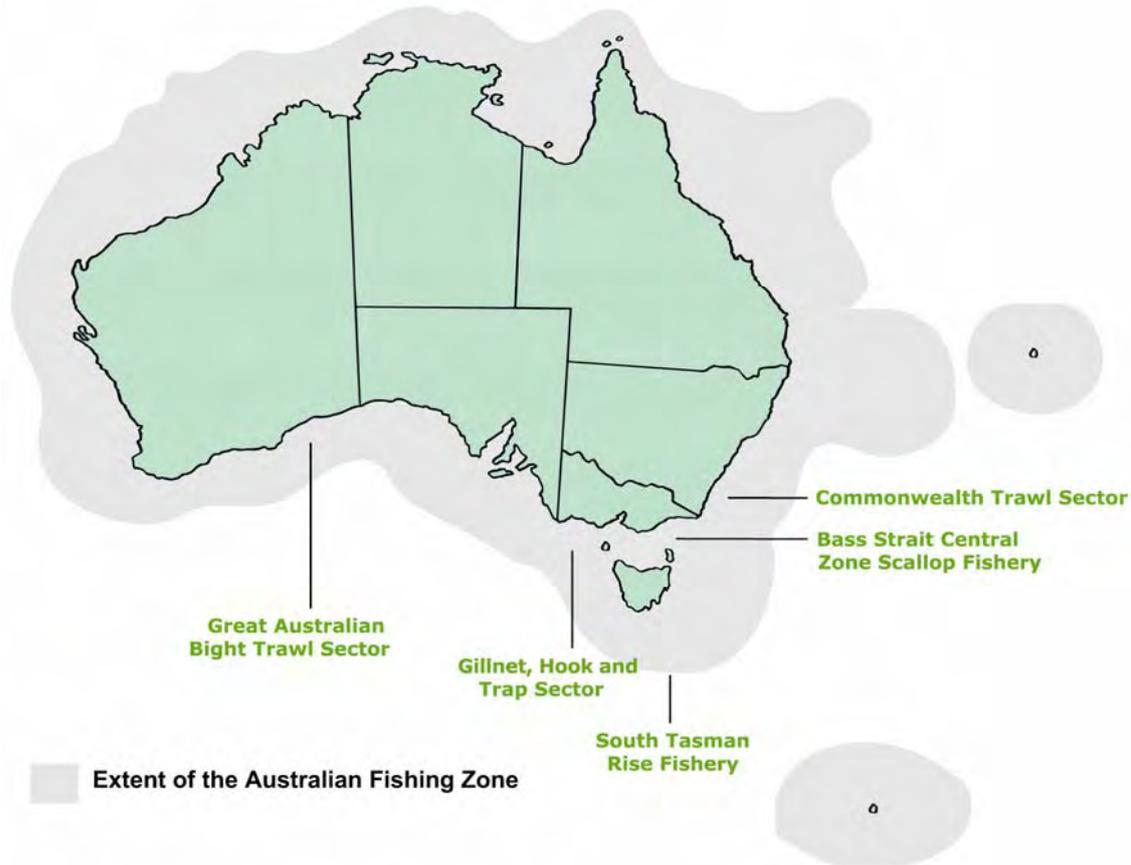
Figure 4.1 South-east demersal fisheries. Figure modified from http://www.afma.gov.au.

Overview

The south-east region of Australia has an extremely diverse fishery (Figure 4.1) that can be divided biologically and economically by depth (coastal [0-50 m], shelf [50-200 m], slope [200-700 m] and deepwater [> 700 m]), by gear type/fishery (e.g. southern shark, demersal trawl, scallop dredge, rock lobster, squid), and by management jurisdiction and agency (State-managed fisheries versus those managed by the Australian Government). The region also has the longest European fishery-history in Australia, has the highest numbers of commercial species, and is also one of the most heavily exploited regions in Australia. In the 2006 annual report on the state of Australia's fisheries, the Australian Bureau of Rural Sciences (2007) listed 19 Australian Government-managed stocks nationwide to be overfished; 11 of these are in the south-east demersal fishery group (Larcombe & McLoughlin 2007). Despite this, the fisheries are still amongst the most valuable groups in Australia. In 2005/06 the combined value of the Tasmania, Victoria, New South Wales and Australian Government wild fisheries catch in the south-east region (other than pelagic fisheries) was about A\$700m: A\$240m from molluscs (primarily abalone), A\$100m from crustaceans (primarily crayfish) and A\$136m from fish (ABARE 2007). The most valuable fisheries - those for molluscs and crustaceans - are mainly inshore and on the shelf. Due to their proximity to major urban centres in south-east Australia, the socio-economic value of the south-east fisheries is substantial.

Biological Relationships to Environmental Variables

Temperature and solar radiation

As discussed in the first section of this review, global climate change models predict that sea-surface temperatures off south-eastern Australia are likely to be particularly sensitive to climate change, due to the likely effect of a poleward shift in zonal winds on the poleward extent of the warm East Australia Current (Cai, et al., 2005). The results of these models are consistent with sea-surface temperature data from the Maria Island (Tasmania) coastal station, maintained by CSIRO since the early 1940s (Ridgway 2007). Summer sea-surface temperatures at Maria Island have risen by over 1°C over the last 60 years (Figure 4.2).
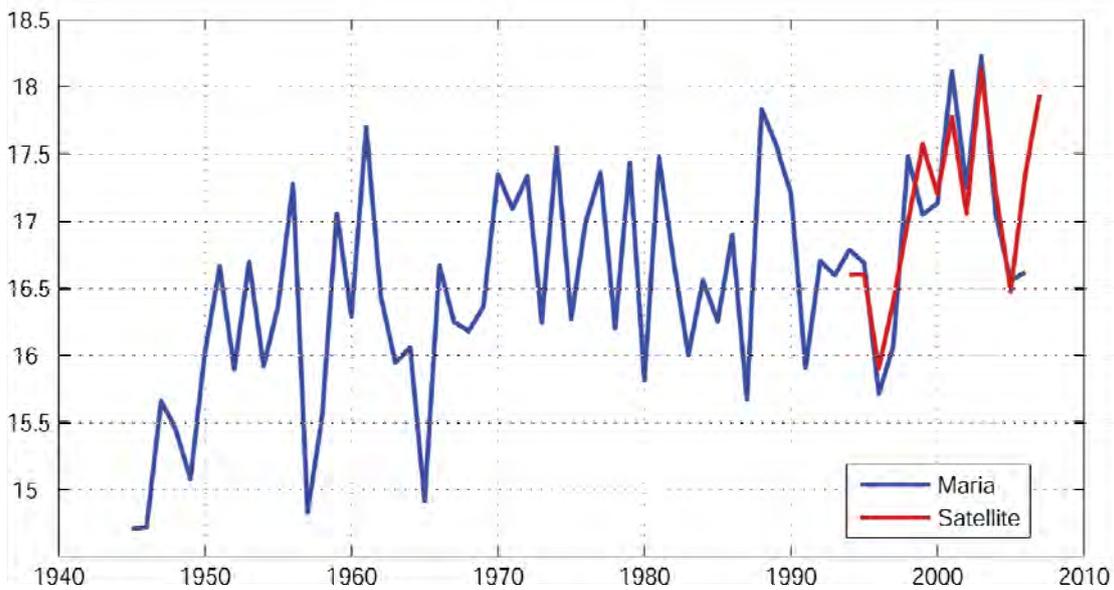
Figure 4.2 Summer (January, February, March) mean sea-surface temperature (SST) at the CSIRO Maria Island coastal station (east coast Tasmania). Red line shows the temperature from satellite observations.

These observations are consistent with multi-century records of deep-water temperature off Tasmania inferred from changes in the composition of deep-water corals (Thresher et al. 2004), though the coral records also suggest the warming trend started well before the onset of anthropogenic warming. The signature of early warming is controversial at this stage, and deserves additional investigation at a wider range of sites in the Tasman Sea.

The poleward shift in the zonal winds regionally predicted by the models also appears to be consistent with recent changes in the Antarctic Oscillation Index, which suggests a contraction of the westerly wind vortex in the Southern Ocean (Gillett & Thompson 2003; though see also Jones & Widmann 2004).

Biological impacts of regional warming due to global climate change are likely to be very substantial in the south-east region, and indeed may well be the most pronounced in any marine region in Australia, for two reasons. First, to the extent that strong recruitment in many local marine species depends on persistent zonal west winds, the predicted poleward shift in zonal wind bands is likely to lead to a general weakening of those winds and hence widespread poor recruitment for both fished and non-fished

marine populations. Second, the models predict that sea surface warming around Australia as a result of climate change will be largest in the south-east, which will have profound effects on the distribution of many species (the distribution of marine invertebrates, in particular, is often strongly affected by water temperatures). As a result, we can expect to see major changes in species distribution, community composition and ecosystem function. For examples of similar patterns in the northern hemisphere, see Perry et al. (2005) and Brodeur et al. (2006). Unlike Northern hemisphere scenarios, however, the east-west orientation of the temperate Australian coastline means there are few opportunities for species to move south as water temperatures increase (Poloczanska et al. 2007).

Although few detailed studies have been undertaken to date, some quantitative data and a diverse range of qualitative data suggest these impacts are already being felt. Some examples include the following:

- Juvenile growth rates of shallow water, commercially exploited fish species in the south-east have increased significantly since the early 20th century, based on historical analysis of the width of annual increments in their otoliths (Thresher et al. 2007).   The changing growth rates do not appear to reflect changes in the abundance of the fish (due to effects of fishing, for example), but rather correlate significantly ($p < 0.01$) with the Maria Island temperature time series (Figure 4.3), paralleling both the long-term trend and shorter trend variability around the trend line. This increase is restricted to shallow water species; among deeper (>1000 m) species examined, growth rates have been falling, paralleling declining water temperatures at intermediate depths. An effect of water temperature on growth rates is not surprising, as water temperature is one of the principal determinants of growth rates in fishes, as in other poikilothermic species. Consequently, increased growth rates could be widespread among shallow water marine species in south-east Australia. The consequences of such changes on population and community dynamics have not yet been examined.

- Range extension by *Noctiluca* (a nonphotosynthetic dinoflagellate) has been observed to southern Tasmania. Surveys of phytoplankton around Australia prior to 1964 reported *N. scintillans* (as *N. miliaris*) only sporadically from NSW and Victoria, commonly in Moreton Bay (28°S). More recently it has been found blooming extensively off New South Wales (34°S, Dela-Cruz et al. 2002, 2003). *N. scintillans* started to move into Tasmania with the EAC from 1994, and became an overwintering resident in Tasmania around 2003 (Ajani et al. 2001).

- The long-spined sea urchin, *Centrostephanous rodgersii*, an important habitat modifier in New South Wales, crossed Bass Strait in the mid-1960s and was first discovered on the east coast of Tasmania in 1978 (Edgar 1997). The poleward shift in the distribution of this species has been associated with the decline of urchin barrens on the NSW coast, which adversely affected the local abalone fishery, while its arrival in Bass Strait and subsequent spread along the east coast of Tasmania has led to development of extensive urchin barrens in areas where they did not previously exist. The arrival of *C. rodgersii* off Tasmania appears to be disrupting the existing balance between macroalgae, abalone, rock lobsters and the native urchin, which apparently accounts for a negative relationship between the abundance of *C. rodgersii* and the density of

commercially fished abalone and rock lobster. It is predicted that without management intervention, *C. rodgersii* barrens will eventually cover 50% of the rocky reef habitat on Tasmania's east coast and have serious implications for the sustainability of rock lobster and abalone fisheries (Johnson et al. 2005). As noted above, these are among the most valuable fisheries in the south-east region.
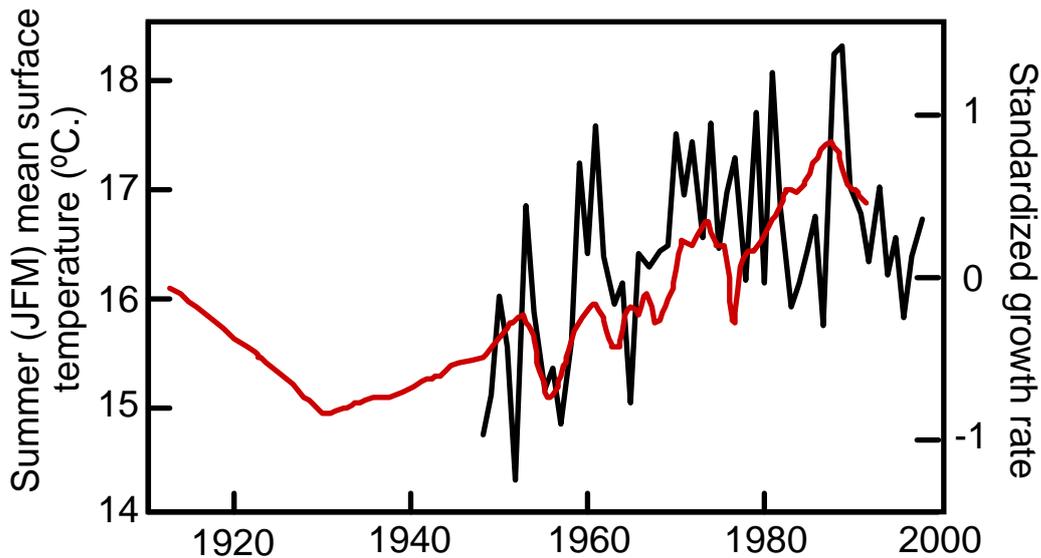
Figure 4.3 Comparison of surface (10 m) summer (JFM) mean temperatures at the Maria Island oceanographic station (black line) and historical variability in juvenile growth rates, pooled, for three shallow water fish species in south-east Australia (red line) (from Thresher et al. 2007).

- In the last decade, there have been conspicuous changes in the distribution of Tasmanian marine fishes. Some 36 species in 22 families (about 10% of the inshore families of the region) have exhibited major distributional changes: some have become newly established south of Bass Strait; others have markedly increased in abundance in southern Tasmania, by shifting their ranges south along the Tasmania coast; and others are totally new records for Tasmania (P. Last, in Lyne 2005). Most of the species exhibiting a clear poleward shift in distribution are reef species, mainly western warm temperate (Flindersian) or eastern warm temperate (Peronian) species. Many are normally found off the NSW coast, in habitats also associated with the urchin *Centrostephanus rodgersii*.

- The European shore crab *Carcinus maenas* was first recorded in Port Phillip Bay, Victoria, in the late 1800s, apparently introduced in the dry ballast of wooden vessels from Europe. In the hundred years since, it has become widely distributed throughout Port Phillip Bay, and along the south-east coast of Victoria and southern New South Wales, with a small, disjunct population in South Australia. Its overall distribution on the temperate Australian mainland coast has been essentially stable for the last century. In 1993, it was discovered in north-eastern Tasmania (Gardner et al. 1994). Between 1993 and

2002, it became well established on the north and northeast coasts of Tasmania, but was apparently absent from areas farther south (Thresher et al. 2003). In 2002, this changed rapidly: in a single year it spread to populate the entire east coast of Tasmania (Thresher & Gurney, in prep.). *C. maenas* is an aggressive inshore predator and the spread has coincided with a decline in the abundance of native bivalves in subtidal areas, and virtual elimination of many native Tasmanian inshore crab species; both groups are heavily preyed upon by the European invader (Walton et al. 2002).

Winds, currents, MLD & stratification

Despite the fisheries' long history, the effects of climate on marine stocks in the south-east region have not been well studied. Most of the work and speculation have been on the effects of wind. In some years, strong wind events have been linked to larval growth rates and/or recruitment of juveniles in two fish species: one coastal rocky reef fish (*Heteroclinus* sp.; Thresher et al. 1989) and one commercially fished gadoid found on the outer shelf (*Macruronus novaezelandiae,* blue grenadier; Thresher et al. 1992). More broadly, Harris et al. (1988) reported quasi-decadal variability in the frequency each year of strong zonal west winds over south-east Australia and related this variability statistically to catch rates and recruitment variability in a number of fisheries in the south-east region, ranging from brown trout in an inland lake to rock lobster and southern bluefin tuna. Thresher (2002) subsequently extended the wind time-series another decade, and showed, first, that the quasi-decadal cycle was also reflected in regional winter rainfall, and second, that it appeared to reflect variability in solar radiation (the sunspot cycle). A roughly ten-year cycle, in several cases directly linked to regional wind, has been reported in a variety of south-eastern stocks (Figure 4.4), including year-class strength in scallops and abalone, recruitment in a number of shelf teleosts (Thresher 2002, Jenkins et al. 2005) and even in the stranding frequency of cetaceans (Evans et al. 2005). Thresher (1994) suggested that the collapse of the gemfish fishery off south-east Australia was due to the combination of declining winds resulting in the periodic fall in recruitment, and the effects of over-fishing, which had depleted the spawning stock. To date, no studies have explicitly investigated the mechanisms relating the zonal winds and recruitment variability in south-eastern stocks, though it has been speculated that the winds are affecting either or both larval transport or coastal productivity (Harris et al. 1988, Jenkins 2005).

Shorter period variability (7-8 years) in recruitment has long been reported for the shelf-dwelling gadoid (blue grenadier, *Macruronus novaezelandiae*), which spawns in south-eastern Australia. This information has recently been synthesised and analysed in more detail by Klaer and Tuck (unpublished data), who noted evidence of a similar periodicity in Patagonian toothfish at Macquarie Island. How these 7-8 year cycles in biology are related to regional oceanography and climate is not known.
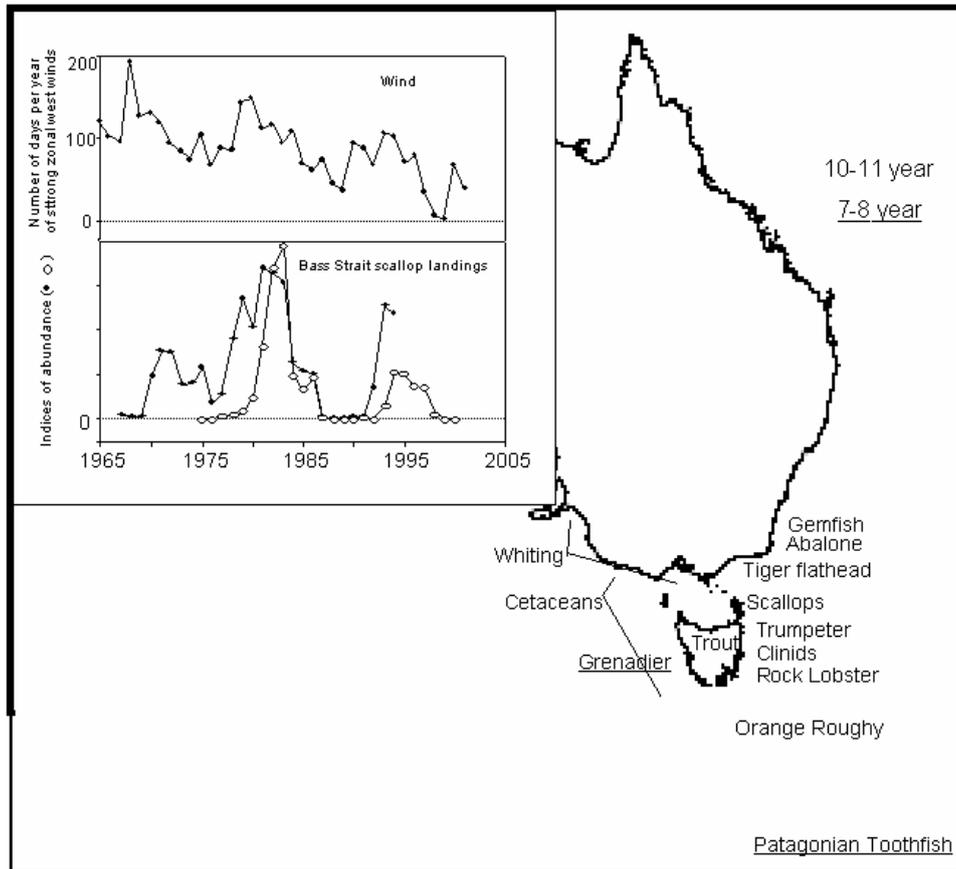
Figure 4.4 An example of quasi-decadal variability in a south-east fished stock – Inset: two complementary indices of landings of scallops in Bass Strait, lagged to recruitment year based on the mean age of the catch, compared with regional variability in the persistence each year of zonal west winds. The larger figure shows the distribution of some south-east stocks that have been reported to vary periodically at either 7-8 year (underlined stocks) or 10-11 year intervals. From Thresher (in prep).

Precipitation, extreme events, and terrestrial runoff

The impacts of changes in freshwater flows will not be significant for the open sea species; however, for species that rely on inshore habitats, such as estuaries, consequences may arise. Flushing of estuaries may impact breeding migrations, spawning habitats, nursery areas, and the suitability of those habitats to support existing commercial species. Fisheries that may be affected include those based on shelf species that use inshore areas as nurseries, such as jackass morwong, blue grenadier and King George whiting (Jenkins 2005), as well as those resident in coastal regions, such as abalone and rock lobster. Changes in storm frequencies and run-off patterns could also impact those species dependent on detrital food chains, such as blue grenadier larvae (Thresher et al. 1992, Davenport & Bax 2002).

Sea level rise

The impacts of sea level rise will not be significant for the open sea species; however, those species that rely on inshore habitats, such as estuaries, may be affected. Inshore habitats are important nursery areas for a number of important south-east commercial species, including snapper (Bell et al. 1991), school sharks (Williams & Schaap 1992), jackass morwong (Thresher et al. 1994) and whiting (Jenkins 2005).

37

Acidification (CO_2 and pH)

The impacts of ocean chemistry changes on the exploited species of the south-east have not been assessed.

Impacts of Climate Change on South-east Demersal Fisheries

The effects of climate change on the south-eastern fisheries have also not been studied, though there has been considerable speculation on likely effects, in part because of the wind effects on recruitment noted above, in part because of conspicuous coastal warming in the south-east, and in part because of anecdotal information suggesting a substantial poleward shift in the shallow-water marine biota of the south-east over the last decade. This information was synthesised and discussed in detail by Lyne et al. (2005), reporting on the outcomes of a CSIRO workshop on potential effects of climate change on south-east marine communities.

Socio-economic impacts

Ecosystem and fisheries impacts of these changes are already being felt. As noted above, abalone and rock lobster abundance is declining in areas of Tasmania where

Image credit: Alistair Hobday

the NSW urchin, *C. rodgersii*, is establishing barrens. The introduced shore crab *C. maenas* preys extensively on, and largely eliminates cockle clams from invaded areas: cockle clams support a small inshore fishery in Tasmania (Walton et al. 2002). The crab is also fundamentally altering the trophodynamics of shallow subtidal areas, with as yet unknown consequences for commercial species that use such areas, including seagrass habitats, as nurseries. Kelp beds, a major marine community once extensive along the coast of Tasmania and an important habitat for a wide range of commercially fished species, have disappeared in many locations along the coast (Edyvane 2003). The gemfish fishery, already under pressure from apparent over-fishing (like many of the south-east stocks), collapsed altogether when the zonal winds declined to their predicted low point in the 10-year cycle (1989). In fact, the zonal winds in this year were at the lowest levels ever reported. Since then, the winds have fallen further, perhaps reflecting the predicted onset of overall weak zonal winds in the south-east region due to climate change, and also perhaps explaining why, despite the fishery being closed, there has been little or no sign of recovery of the eastern gemfish stock (Caton & McLoughlin 2004). Observations of an increase of juveniles in 2003/04, based on incidental catches, have been interpreted as suggesting improved recruitment (Larcombe & McLoughlin 2007), which would be consistent with an increase in the persistence of the zonal west winds during that period.

More broadly, the predicted high sensitivity of south-eastern sea-surface temperatures to climate change could have a devastating effect on local biodiversity and the capacity of local ecosystems to support productive fisheries. The poleward shift in marine fishes has already been noted, but fish are unlikely to be the only group affected. By comparison with other marine taxa, fish are well studied taxonomically

and the larger species easily recognised and noted by recreational and scientific divers. Consequently, we would expect any change in distributions to be noted first for this group. The poleward shift in distribution of two other large and easily recognised invertebrate species - the European shore crab and the barren-forming urchin - strongly suggests many other marine invertebrates, which are less easily recognised, are also shifting their ranges polewards.

Industry adaptation capability

This fishery region has a long history, and in that time there have been fluctuations in the exploited species. Fishers have had to cope with changes in abundance and distribution of key species (Smith & Smith 2001). Climate change impacts on biota could affect fisheries management in several ways. For example, the Commonwealth harvest strategy policy sets certain benchmarks to define overfishing, including biomass limit reference points. These could well change as productivity or distribution change, with significant impacts on quotas and effort levels given the direct link between the benchmarks and management decisions. The guidelines to the policy already envisage that account should be taken of changing benchmarks, but the difficulty will be in detecting the effects and determining the changes. Another management issue is that most fisheries are defined by jurisdictional boundaries that determine access and property rights. As species distributions change, some fishers' rights may diminish, while other fishers currently without species access rights may gain effective access to the fish.
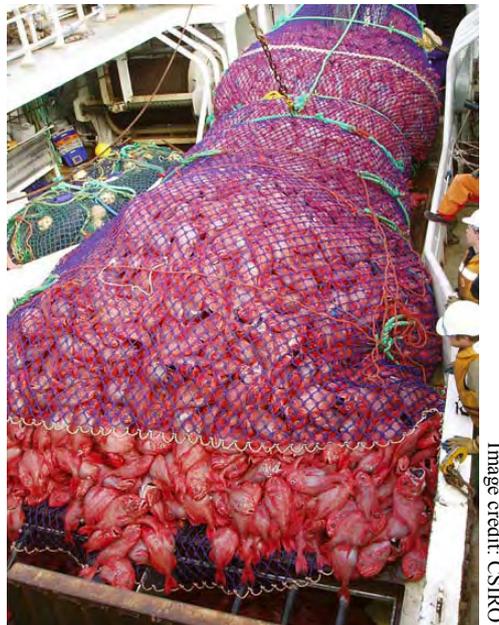
Image credit: CSIRO

Key Points: South-east Demersal Fisheries and Climate Change

This region is perhaps the best studied with regard to climate variability, though information is still patchy.

Physical

- Warming off the east coast of Australia has already been documented, in agreement with climate model predictions.

- Wind relationships have been linked to the recruitment of several species – although the mechanisms are not clear.

Biological

- Potential positive and negative impacts on different species recruitment due to dependence on persistent zonal winds and the change in ocean temperature.

- Correlations between changing ocean temperatures and growth rates, meaning enhanced growth for some species.

- Ecosystem impacts attributed to climate and declines in the abundance of key species have been documented. Examples include declining productivity of abalone and rock lobster fisheries, reduction of kelp beds and failure of gemfish stocks to recover from overfishing.

Socio-economic

- A number of stocks in this region are over-exploited; the additional impact of climate change is of concern to future sustainability.

- Increased temperatures at the southern end of species' ranges leaves little room for further southward migration, thus fishers will likely be affected.

5. Western Fisheries

Figure 5.1 Western fisheries. Figure modified from http://www.afma.gov.au.

Overview

Western fisheries (Figure 5.1) harvest demersal, coastal and pelagic species. The coastal and demersal segments are treated in this section; the pelagic species are covered in the pelagic fisheries section. The demersal fisheries dominate with respect to landings and value, and the main species harvested are invertebrates. The relatively high catch of invertebrate species in Western Australia compared to finfish is in sharp contrast to other regions of the world, where finfish production usually dominates (Lenanton et al. 1991, Pearce & Caputi 1994). This low level of finfish production is primarily due to the Leeuwin Current, which brings warm, low-nutrient waters southward along the edge of the continental shelf of the Western Australian coast (Lenanton et al. 1991). West coast fisheries (excluding commonwealth fisheries) account for 29% (~A$542 million) of the Australian fisheries production value (ABARE 2007).

The principal invertebrate caught in Western Australia is the western rock lobster, *Panulirus cygnus*. It supports Australia's most valuable single-species fishery. The fishery targets the rock lobster on the west coast of Western Australia between Shark Bay and Cape Leeuwin, using baited traps (pots). Annual production, which averages in excess of 11,000 t, is worth $250-350 million (ABARE 2007). In 2005/06 the value was A$292 million and 10,435 t was captured (ABARE 2007). The other important species include prawns (A$38 million), abalone (A$12 million) and scallops (A$9 million) (ABARE 2007).

A focus on one species, the rock lobster, is pertinent, as it illustrates the interaction between the environment and the life history characteristics of an exploited species. The life cycle of the rock lobster begins with the hatching of eggs in late spring and summer (mostly December-January) on the outer continental shelf. The larvae then disperse to the open ocean to spend some 9 - 11 months in an oceanic larval phase, during which mortality is high. They then return to the coast from about July onwards as the final 'puerulus' larval stage. The number of pueruli settling has been monitored for decades; annual settlement can vary more than five-fold (Griffin et al. 2003). Fluctuations in commercial catches are due primarily to variations in puerulus settlement three and four years before the season in which the catch is taken. Interannual variability in puerulus settlement gives rise three to four years later to variations of ± 2,000 t in the commercial catch (Caputi et al. 1995). Levels of pueruli settlement have become the main tool used to manage the fishery.

Biological Relationships to Environmental Variables

The majority of understanding about the relationship between the environment and biology has focused on the most valuable species, the western rock lobster. In the following sections, additional species are discussed where information is available.

Temperature and solar radiation

The influence of ocean temperatures along the west coast of Australia is expressed through changes in the Leeuwin Current. Accordingly, the discussion of temperature cannot be separated, and so most information is presented in the next section.

Water temperature affects the period that eggs are retained by female rock lobsters before the larvae hatch. Growth rates of several species have also been linked to temperature changes (e.g. rock lobster larvae: Liddy et al. 2004).

Winds, currents, MLD & stratification

The major influence of the Leeuwin Current on recruitment of fished species is during their larval phase (Lenanton et al. 1991, Caputi et al. 1996). The strength of the current has a significant positive influence during the larval stage of the western rock lobster, but a negative influence on the larval life of the scallop *Amusium balloti* in Shark Bay and at the Abrolhos Islands (Pearce & Capuiti 1994). For pelagic finfish species, the current has an adverse effect on the survival of pilchard larvae (*Sardinops sagax neopilchardus*), but a positive impact on whitebait (*Hyperlophus vittatus*) and also on recruitment of Western Australian salmon (*Arripis truttaceus*) and Australian herring (*Arripis georgianus*) to South Australia (Pearce & Capuiti 1994). The current appears to have a correspondingly negative impact on the recruitment of Australian herring in the south-west of Western Australia. Possible mechanisms for the effect of the Leeuwin Current include transportation of larvae and temperature effects on spawning success, as well as survival and growth of larvae. Again, the majority of research has focused on the rock lobster.

Griffin et al. (2001a, 2001b) tested the hypothesis that the advective and dispersive effect of the Leeuwin Current was the mechanism responsible for the positive relationship between the strength of the Leeuwin Current and levels of puerulus settlement. They computed year-long trajectories of model larvae, using estimates of ocean current velocity for six actual years derived from Topex/Poseidon and ERS satellite altimeter data, and the known information on the diurnal vertical migration behaviour of the larvae. The model demonstrated that large numbers of larvae could

return to the coast despite the strong southward current, due to the opposing effect of the wind and current. The model was also in general agreement with research observations of the distribution of larvae in the open ocean. It also showed that many late-stage larvae were carried south of the fishery in years when the Leeuwin Current was strong. This has been confirmed by examining the relationship between the current's strength and mean latitude of puerulus settlement (Caputi et al. 2003). However, the model failed to produce large inter-annual fluctuations in the number of pueruli settling, even though the effects of the waxing and waning current were evident in the velocity estimates. While it is possible that the details of the advection process were not adequately modelled, the Griffin et al. work suggests that puerulus settlement is controlled by other environmental parameters not included in the model.

Explanations for the positive relationship between Leeuwin Current strength and levels of puerulus settlement have shifted from the direct influence of ocean currents in transporting larvae to the indirect influences on their growth and mortality. The available information suggests two hypotheses. Firstly, laboratory tests indicate that the warmer waters associated with a stronger Leeuwin Current could help the growth and survival of the larvae. Secondly, the south-flowing Leeuwin Current may increase larval retention by eddies and assist in the transport of the late-larval stages and puerulus across the continental shelf into coastal reef nursery areas, especially in the southern areas like Cape Mentelle (Caputi et al. 2001, 2003).

At present, there is no need for short-term predictions of El Niño events for management of this fishery because the impact of El Niño is on the larval stage rather than on the adults, so the effects are delayed for three years. However, the five-fold variability in larval settlement clearly demonstrates that environmental variability significantly influences the rock lobster fishery. Hence the fishery is susceptible to climate variability and a response to climate change would be expected.

Other Western Australian fisheries also correlate (some positively, some negatively) with phases of the El Niño-Southern Oscillation (ENSO) and the strength of the Leeuwin Current through unknown mechanisms (Penn et al. 2005). For example, pearl oyster (*Pinctada maxima*) catch rates are affected by a number of environmental variables including El Niño events: catch rates were enhanced two years after El Niño events (Hart et al. 1999).

Precipitation, extreme events, and terrestrial runoff

Species that occupy inshore habitats are likely to be impacted by changes in freshwater flows. Estuaries are important feeding and breeding grounds for a number of commercially exploited west coast species, such as blue swimmer crabs (*Portunus pelagicus*), western prawns, sea mullet (*Mugil cephalus*) and western sand whiting (*Sillago bassensis*) (Fletcher & Head 2006).

The variation in tiger prawn recruitment in Exmouth Gulf is either positively or negatively influenced by cyclones, depending on their strength and timing (Penn & Caputi 1986, Penn et al. 1997). A cyclone in 1999 also affected the seagrass habitat of juvenile prawns, which resulted in low recruitment in 2000 and 2001. The frequency of cyclones is influenced by ENSO events but the future pattern of ENSO is not known.

Storms also result in the detachment of macroalgae, and a number of species rely on these nearshore aggregations of detached algae for summer feeding (Yellow-eye mullet, *Aldrichetta forsteri,* Cobbler *Cnidoglanis macrocephalus,* whiting *Sillago*

bassensi, and West Australian salmon *Arripis georgianus*: Lenenton et al. 1982). An increase in storm activity above the level necessary to create algal drifts may disrupt these nearshore feeding grounds.

Sea level rise

Variation in coastal sea level has been important for species captured in west coast fisheries. This interannual fluctuation is a result of variation in Leeuwin Current strength, which is influenced by El Niño-Southern Oscillation events, rather than sea rise due to climate change. Pearce and Phillips (1988) first noticed that coastal sea level (an indicator of Leeuwin Current strength) was correlated with settlement rates of puerulus. During La Niña events, sea level is high throughout the western equatorial Pacific, and as this signal propagates down the west coast of Australia it heralds a stronger-than-usual, southward-flowing Leeuwin Current and high rates of puerulus settlement. Conversely, the Leeuwin Current is weak during El Niño events and puerulus settlement is low. Westerly winds associated with winter/spring storms in the months just before and during the settlement period were also shown to impact the level of settlement.

Image credit: Alistair Hobday

Sea level rise due to climate change may impact coastal habitats important as breeding or nursery areas. Commercial species that use coastal habitats include pink snapper (*Pagurus auratus),* southern sea garfish (*Hyporhamphus melanochir*), Australian herring (*Arripis georgianus*), whiting and mullet (Fletcher & Head 2006).

Estuarine species along the south-west coast may also be vulnerable to loss of shallow habitat; the important commercial species include black bream, cobbler, mullet and whiting (Fisheries Management Paper 126).

Acidification (CO_2 and pH)

There are no studies on the relationship between ocean acidification and the species targeted in western fisheries. As for other regions, it is likely that changes in ocean chemistry will impact the lower trophic levels (phytoplankton and zooplankton) and eggs and larvae of exploited species.

Impacts of Climate Change on Western Fisheries

Socio-economic impacts

The fluctuation in value of the rock lobster catch, which is related to environmental variation, indicates that socio-economic effects can be large. Under various climate-change scenarios, changes in the frequency of El Niño and the strength of the Leeuwin Current may directly impact the rock lobster fishery. It is not known whether the species' spawning strategy would adapt to a sustained shift to a weaker Leeuwin Current and warmer temperatures. Further, it is unclear whether these

mechanisms would continue to operate under the combined influence of a sustained weaker Leeuwin Current (which would tend to reduce temperatures) and the regional rise in sea-surface temperature along the coast of Western Australia due to global warming. A major concern is that climate change might cause a systematic shift in the larval settlement–Leeuwin Current relationship, which could invalidate the present management approach. The combination of ocean warming and changes in the strength of the Leeuwin Current might increase the growth rate of larvae, changing their time of settlement. By investigating and identifying the mechanistic link between the Leeuwin Current and puerulus settlement, one would obtain the essential information to assess climate-change impacts on the rock lobster fishery. Such work would be critical to addressing the impacts of climate change within the management framework of the rock lobster fishery and to ensuring a sustainable fishery into the future. Research on the Leeuwin Current-rock lobster link would also benefit other fisheries in Western Australia.

Industry adaptation capability

The rock lobster industry already copes with significant interannual catch fluctuations, as discussed earlier, and utilises a catch prediction system that allows industry to prepare for harvests several years ahead. Salmon abundance also varies along the southwest coast, and boom and bust years also occur in the scallop sector. These features, however, are not desirable to many involved in west coast fisheries. Climate change may lead to additional changes in the alternative species harvested when the primary species is less available. Thus, the robustness of the west coast fishery sector may decline in the future if climate variability increases, as variation in catch between years will increase. Interaction between the commercial and recreational sector and other marine users are also resulting in zoning that excludes fishing activities in some areas (e.g. recreational fishing zones, marine protected areas). As changes in fish distribution occur, commercial fishers may not be able to simply follow the stocks, as they may contract into different management regions. As with the other fishery regions considered, information on the potential changes will enhance industry capability to adapt to climate change, and make sensible business and investment decisions.

Image credit: Alistair Hobday

Key Points: Western Fisheries and Climate Change

The west coast is an oligotrophic region dominated by invertebrate fisheries, including Australia's most valuable fishery, the western rock lobster fishery (A$250-350 million per year).

Physical

- The Leeuwin Current may weaken slightly, which would lead to cooler temperatures along the southern coast; however, warming of surface waters is also likely due to general climate warming. The overall outcome with regard to sea surface temperature in this region is uncertain.

- The relationship between ENSO events and the Leeuwin Current is variable, and so extrapolating from climate variability patterns to climate change is problematic.

Biological

- The Leeuwin Current has a strong link with recruitment for many species.

- Understanding the mechanism that leads to recruitment variation associated with the Leeuwin Current will enhance understanding of climate impacts for a number of species, including the valuable western rock lobster.

Socio-economic

- Changes in species distribution and increased climate variability mean flexible policies are needed to allow the commercial fishing industry to adapt to climate change.

6. Pelagic Fisheries

Figure 6.1 Pelagic fisheries. Figure modified from http://www.afma.gov.au.

Overview

The main pelagic fisheries in Australia (Figure 6.1) are managed as three separate fisheries, although the target species are the same or similar in all three fisheries. Tuna (yellowfin, bigeye, albacore and southern bluefin) and billfish (broadbill swordfish, striped marlin) are the main target species in the eastern and western longline fisheries (ETBF and WTBF), while southern bluefin tuna is the single target species in a purse seine fishery in the Great Australia Bight (SBT fishery). A second purse seine fishery for skipjack tuna was recently separated from the ETBF for management purposes, although it remains small in value and tonnage (Larcombe & McLoughlin 2007).

The gross value of production in the ETBF in 2005/06 was A$28.7 million, down from A$42.5 million in 2004/05 (ABARE 2007). This decline was due to a reduced catch of some species e.g. swordfish, lower prices due to a strengthening Australian dollar, as well as a shift to lower value species (albacore). Whether this pattern is related to changes in the regional oceanography is not clear, as fishing practices were also altered to target deeper-living albacore. However, the impact of overfishing on swordfish in particular cannot be ignored. Declines in value for the other fisheries were relatively minor at 3% (WTBF: 2005-06 A$2.7 million) and 4% (SBT: 2005-06 A$37.5 million, wild caught value), and related to prices for the key species (ABARE 2007).

Two lower value, but high-volume, fisheries - the small pelagic midwater trawl fishery (SPF) and the southern squid jig fishery (SSJF) - are also covered in this section, as the target species in each are found in the upper water column on the continental shelf. The SPF comprised 12 active vessels in 2006, catching a combined

11,000t of the three target species redbait, blue mackerel and jack mackerel (Larcombe & McLoughlin 2007). The value of the SSJF catch was approximately $1 million (619 t) in 2006, and squid are also captured as a byproduct in several trawl fisheries (949 t) (Larcombe & McLoughlin 2007).

The two pelagic longline fisheries have a large number of byproduct and bycatch species, which may also experience climate-related impacts, while the two lower value fisheries (SPF and SSJF) target key species at intermediate trophic levels. These intermediate levels contain crucial species for the rest of the ecosystem and could be particularly sensitive to climate impacts (e.g. Cury et al. 2000, Rose 2005, Hunt & McKinnell 2006). Pelagic squid, which make up the SSJF, have more flexible life history strategies and greater tolerances to environmental change than the fishes making up the SPF (Pecl & Jackson 2005). They could therefore benefit from climate induced changes in the regional oceanography, possibly at the expense of the species of the SPF which feed mainly on zooplankton that are restricted to temperate waters (Young et al. 1993). In the Eastern Tropical Pacific Ocean, there has been an expansion in the range and increase in abundance of the jumbo squid, *Dosidicus gigas*. The jumbo squid expansion has been linked to the collapse of the shortbelly rockfish *Sebastes jordani,* which is also a prey of the squid (Field & Baltz 2007). Although the cause of the increase in these squid is unclear, warming of the regional oceanography has been implicated (Olson & Young 2007).

There are no studies that have considered the impact of climate variability or change on pelagic species' phenology or physiology or community membership. In Australian pelagic systems, the limited evidence of links to climate variability has been gathered for abundance and distribution changes and changes in ecosystem productivity; these are discussed further below.

In general, information on stock status (abundance and distribution) has come from catch data, while much of the fishery-independent data on the environmental associations of large pelagic species has been gathered by electronic tags. These tags will continue to provide unique insight into habitat preferences and utilisation and form the basis for future climate-impact studies. In particular, data from these tags are being used to understand the movement and behaviour of fishes in response to climate forcing at a variety of temporal and spatial scales. Electronic tags remain one of the best tools to understand the movement and behaviour of larger species in the pelagic realm.

Biological Relationships to Environmental Variables

Temperature and solar radiation

Temperature of the ocean has a demonstrated effect on the distribution of the target species in Australia's pelagic fisheries (SBT: Reddy et al. 1995). Evidence is also strong in other parts of the world, and temperature is one of the strongest drivers of pelagic fish distribution (Laurs et al. 1984, Andrade & Garcia 1999, Schick et al. 2004, Kitagawa et al. 2006). The strongest environmental signal in the ocean, the ENSO phenomena, has been shown to have a major impact on the distribution of tropical tunas (Lehodey et al. 1997).

On the east coast, pelagic species are captured in the Coral Sea, East Australian Current and Tasman Sea regions. There are seasonal changes in the abundance of species, such as yellowfin (*Thunnus albacares*) and bigeye tuna (*T. obesus*), captured

in the longline fishery that are positively linked to the expansion and contraction of the East Australian Current (Campbell 1999). At a finer scale the distribution of yellowfin tuna has been linked to the distribution of mesoscale environmental features, such as eddies generated by the East Australian Current (Young et al. 2001).

Increases in water temperatures will likely result in squids that hatch out smaller and earlier, undergo faster growth over shorter life-spans, and mature younger and at a smaller size. Individual squid will require more food per unit body size, require more oxygen for faster metabolisms, and have a reduced capacity to cope without food (Pecl & Jackson 2005).

While solar radiation will increase and this may impact pelagic eggs and larvae in particular, there are few studies that have considered this variable in the ocean (see Zagarese and Williamson (2001) for freshwater and aquaculture impacts).

Winds, currents, MLD & stratification

The known relationships between the distribution and abundance patterns of some pelagic species on the east coast suggest that changes in the strength of the East Australian Current would have dramatic effects on the availability of key pelagic species to the fishery, although the mobility of the fishing fleets might reduce the immediate economic impact. Changes in productivity can also affect the pelagic ecosystem and the harvested species at the top of the food chain; research in this area is in its infancy (Young & Hobday 2004). Preliminary analyses have found spatial differences in productivity and pelagic ecosystem structure, and it is believed these regional differences could mimic the temporal changes that might occur as a result of climate change.

In the east coast small pelagic fishery (since ~1985), changes in fishing method (purse-seine to midwater trawl) have confounded potential environmental relationships with small pelagic fish distribution and abundance (Lyle et al. 2000) that have been so clearly documented elsewhere in the world (e.g. Chavez et al. 2003, Jacobson et al. 2001). However, off the coast of Tasmania, declining growth rates of jack mackerel and a change in the age structure of the catch through the 1990s may have both an environmental and an anthropogenic component (Lyle et al. 2000, Browne 2005). Changes in the relative dominance of the East Australian Current and the sub-Antarctic water masses, and consequently the regional prey communities have also been implicated in changes in local productivity off the east coast of Tasmania (Young et al. 1993, 1996). For example, the disappearance of krill, *Nyctiphanes australis*, from the shelf ecosystem of eastern Tasmania during a warm (La Nina) event in 1989 was linked to the simultaneous disappearance of their main predator, jack mackerel (*Trachurus declivis)* (Young et al. 1993). Given that *N. australis* is at the base of most Tasmanian shelf marine ecosystems, and that it is a cool-water species, any persistent warming of the regional oceanography would have a profound effect on krill-dependent food chains. These food chains include cephalopods (Pecl & Jackson 2005), seabirds (Bunce 2004), small pelagic fish and tunas (Young et al. 2001).

In southern Australia, juvenile southern bluefin tuna (SBT) have been the subject of several studies investigating distribution and abundance relationships to mesoscale environmental variability (Hobday 2001, Cowling et al. 2003) or to prey (Young et al. 1996). In general, the environmental linkages to abundance are not strong at the mesoscale, although problems with the spatial resolution of some biological data have

confounded analyses. A recent study did not find a link between an apparent decline in a fishery-independent abundance index of age-1 SBT and environmental conditions (SST, Leeuwin Current strength, winds) in south-western Australia (Hobday et al. 2004). This index of abundance has not yet been validated, and so environment-SBT relationships may have been overlooked. In contrast, at a larger scale, seasonal changes in the abundance of juvenile SBT (ages 1-5) in southern Australia are well documented. SBT are resident along the shelf during the austral summer (Cowling et al. 2003) and then migrate south during the winter. Interannual variation in SBT abundance within the main fishing grounds in the Great Australia Bight has not been linked to the environment, although variation in the arrival time of schools has been attributed to unspecified environmental factors (Cowling et al. 2003). Variation in the availability of SBT prey (sardines and anchovies) as a result of changes in wind-driven upwelling (Dimmlich et al. 2004) are also likely if climate change affects the strength of upwelling favourable winds (Hertzfeld & Tomczak 1997), which might ultimately affect the pelagic predators. Finally, the impact of climate change on the winter SBT feeding grounds in the southern ocean may be more dramatic (e.g. Sarmiento et al. 2004); it remains an area for investigation (Hobday pers. comm.).

Image credit: Alistair Hobday

Squid (*Nototodarus gouldi*) catch rates fluctuate in southern Australia, and in some regions and time periods there are links to growth rates and to ocean chlorophyll levels (e.g. Jackson et al. 2003). Regional differences in growth and age/size at maturity may be a result of local environmental differences; the populations may be adapted to local conditions (Jackson et al. 2003, Pecl & Jackson 2005) which makes them vulnerable to climate change. Due to the recent development of the squid fishery in Australia, available catch time-series are too short for demonstrating larger-scale links to processes such as ENSO, which have been shown elsewhere in the world (e.g. Jackson & Domier 2003).

Finally, responses to variability in currents by species captured in the domestic longline fishery on the west coast of Australia have not been documented. This fishery began to decline in 2003, in part due to declines in species catch rates that have been attributed to changes in the oceanographic conditions (A. Hobday pers. comm.); however, there are no studies to date that can link these patterns in variation

of the target species to changes in currents, or any environmental variable. This is in contrast to the nearshore western fisheries, where the influence of the Leeuwin Current is well-established (this review).

Changes in mixed layer depth seem to affect the availability of many pelagic species to fishing gear (Bertrand et al. 2006). For example, when the mixed layer depth is shallow, some pelagic fish concentrated in this layer are more easily captured in purse seine gear. When the layer is deep, the fishing gear will not cover the full depth of the layer. This interaction between environment and fishing gear needs additional investigation.

Precipitation, extreme events and terrestrial runoff

There are no studies on the relationship between precipitation, salinity and storms for the species targeted in Australia's pelagic fisheries. It is expected that in the open ocean, these factors will be of little consequence for pelagic species. The main species are all offshore breeders, and so changes to nearshore habitats are not likely to directly impact the fisheries.

Sea level rise

There are no studies on the relationship between sea level rise and the species targeted in Australia's pelagic fisheries. It is expected that in the open ocean, sea level rise will be of little consequence for pelagic species.

Acidification (CO_2 and pH)

There are no studies on the relationship between ocean acidification and the species targeted in Australia's pelagic fisheries.

Impacts of Climate Change on Pelagic Fisheries

Socio-economic impacts

Overall, the impacts of climate change on pelagic species exploited by Australian fisheries remain unknown. Exploring climate relationships in these offshore regions will be a challenge, due to the short and patchy time-series of pelagic species abundance.

The limited evidence of climate variability impacts in Australian waters coupled with the greater body of evidence elsewhere in the world on the same or related species, does suggest that the impacts will be expressed first in the distribution and abundance of these generally widely distributed and mobile species, such as tuna and billfish. Impacts that result in changes in the other three biological categories - phenology and physiology, composition and interactions within communities, and structure and dynamics of communities - are even more uncertain. Without a greater research effort, an understanding of potential climate impacts and thus the opportunity for adaptation by these valuable Australian industries will be missed.

One example of an industry impact can be provided. Southern bluefin tuna (*T. maccoyii*, SBT) are restricted to the cooler waters south of the East Australian Current and range further north when the current contracts up the New South Wales coast (Majkowski et al. 1981, Hobday & Hartmann 2006). This response to climate variation has allowed real-time spatial management to be used to restrict catches of SBT by non-quota holders in the east coast fishery by restricting access to ocean regions believed to contain SBT habitat (Hobday & Hartmann 2006). This habitat

prediction is based on the relationship between water temperature (from the surface to 200 m) and the abundance of SBT. The current distribution of the tuna habitat is derived with a near-real time ocean model and then relayed to management during the fishing season. As the distribution of the SBT habitat changes during the season, management adjusts the location of restricted access areas throughout the season. This is the only Australian example where environmental information is incorporated into a management response. Changes in the future distribution of SBT (southward contraction) would allow fishers to operate without the particular SBT-restrictions, which may be an economic advantage.

Image credit: Alistair Hobday

Industry adaptation capability

Pelagic fishers have considerable fish finding skills. Their target species roam widely, and are subject to considerable interannual fluctuations in distribution and relative abundance. To counter this variability, fishers use a range of environmental products, such as satellite information from CSIRO and other providers, and sophisticated on-board electronic equipment. These help them to locate suitable conditions for the species that is being targeted.

Fishers also use a range of ports, and change location during the season. Infrastructure may vary between these ports, such as number of berths, storage facilities, ship chandleries, and transport links. Processing facilities and airlinks are considered the main bottlenecks. If ports receive only occasional usage by some boats, then infrastructure is not stretched, however, if major changes in the usage resulted from changed distribution of the catch, infrastructure may prove to be inadequate in new areas.

Changes in the abundance of species that are already at low historic levels (e.g. southern bluefin tuna) can be positive or negative. In the case of increased abundance, rapid industry adaptation will be likely – driven by economic opportunity. It will be a challenge to determine if the change in abundance is likely to be sustained, or is due to interannual variability. This distinction is crucial for long-term business decisions around say, increasing fleet capacity or making technological investments. In the case of declining abundance, industry may be forced to adopt additional management measures to protect a particular species, and so may have reduced flexibility to target the non-impacted species. Improvements in bycatch reduction and improved targeting practises will have the dual benefit of minimising impacts on non-target species, and provide potential alternatives to spatial closures to protect the particular species. Multi-species fisheries should continue to develop species-specific fishing gears and targeting practices to improve future adaptability. Species-specific gears will allow individual species to be targeted, without impacting other species that may be in decline due to climate change, and protected from fishing.

Key Points: Pelagic Fisheries and Climate Change

Physical

- Temperature is implicated as the main driver in climate impacts in the pelagic realm.

- Evidence in Australia and elsewhere has shown these species respond to interannual climate variability:

    o on the east coast, the abundance of several tuna species is linked to the expansion and contraction cycle of the East Australian Current.

    o electronic tags and ocean models have enabled development of predictive habitat models for pelagic species that are used by management.

Biological

- Climate changes in the East Australian Current region are likely to impact pelagic species:

    o A climate-related decline in one mid-level species (jack mackerel) and its cool water prey (krill) has been documented.

    o Squids may grow faster, mature earlier, and require more food resources.

    o Tropical tunas will likely be found further south along the east coast of Australia.

Socio-economic

- Pelagic species are typically mobile and wide-ranging; thus, species' ranges and distribution are most likely to be impacted by climate change. This may mean relocation will be likely for some fishing operations.

7. Sub-Antarctic Fisheries

Figure 7.1 Sub-Antarctic fisheries. Figure modified from http://www.afma.gov.au.

Overview

The major living resources in the Southern Ocean are whales, seals, birds, fish, krill and squid. The exploitation of Antarctic marine resources, which goes back over two centuries (Walton 1987, Agnew & Nicol 1996), has been characterised by progressive over-harvesting by international fleets. The Southern Ocean ecosystem is dominated by krill, *Euphausia superba*, whose biomass may reach 1,000 million tonnes. Commercial fisheries for krill started in the early 1970s (Nicol 2006), although there is considerable uncertainty about krill abundance and trends (e.g. Atkinson et al 2004). Krill landings increased rapidly from 1977 onwards, peaking in 1982 at 607,000 tonnes. They fell in 1983, but peaked again in 1986 (583,000 tonnes) before the fishery collapsed because of lack of profitability and market demand. Between 1991 and 2003, the international krill catch averaged about 80,000 tonnes per year. Krill are caught mainly as food for domestic animals and fish, and are only suitable for human consumption when processed fresh. The international fishery is now relatively small, but most observers expect that to change in the future. Although there

has been a significant krill harvest over the last 30 years (6.6 million tonnes in total), the annual catch has been so far below the level deemed to be sustainable, that any changes observed in krill populations have generally been attributed to factors other than fishing pressure (Croxall & Nicol 2004).

The other main components of the international commercial fish catch in Antarctic and sub-Antarctic waters - Patagonian toothfish (*Dissostichus eleginoides*), other notothenids (icefish), and mackerel icefish (*Champsocephalus gunnari*) - have shown very different developments. Reported international landings of notothenid species peaked in 1970 and subsequently collapsed; for example, stocks of Antarctic cod (*Notothenia rossi*) in the Antarctic Peninsula sector (and, to a lesser extent, mackerel icefish (*Champsocephalus gunnari*) at South Georgia) have failed to recover following over-harvesting. The international icefish fishery started much later, with first reported landings in 1971, before peaking in 1978. Catches after that steadily declined. The international Patagonian toothfish has so far been more successful, with peak catches of 9,000 and 14,000 tonnes in 1990 and 1992, respectively.

Image Credit: Stu Hanchet

There has been relatively little fishing in Australia's EEZ adjacent to continental Antarctica, with fishing restricted to late summer only when sea ice is at a minimum (Hender & Larcombe 2007a). Outside of the high Antarctic, the fishing season is much longer. The Australian fishery for Patagonian toothfish and mackerel icefish around Heard and MacDonald Islands commenced in 1996-1997 (Hender & Larcombe 2007b). Toothfish occur between depths of 300 – 2000m or more and are considered opportunistic predators feeding on mid-water squid, fish and krill as well as benthic fauna (Duhamel & Hureau 1985, McKenna 1991, Goldsworthy et al. 2002). Mackerel icefish are found in shallower shelf waters, generally between 100-350m (Kock 2005), and are a valuable prey species for predators such as elephant seals, Antarctic fur seals and king penguins (Hender & Larcombe 2007b). Recruitment is highly variable in this species. Patagonian toothfish have also been

fished in the Macquarie Island AFZ since 1994 (Hender & Larcombe 2007c). The Macquarie Island region has not been subject to the intensive illegal fishing pressure experienced in Heard and MacDonald Islands region (Hender & Larcombe 2007b,c). There are likely to be considerable changes in these fisheries under the combined pressures of exploitation and climate change. The rest of this chapter focuses on the species harvested by Australian sub-Antarctic fisheries (i.e. not krill fisheries) (Figure 7.1).

Biological Relationships to Environmental Variables

Temperature and solar radiation

Antarctic fish are adapted to stable water temperatures within narrow ranges (Roessig et al. 2004). High-Antarctic fish are adapted to -1.86 to 0.0 ºC while low-Antarctic fish function best in a temperature range -0.5 to 1.5ºC (Kock & Everson 2003). Even a small increase in temperature could have severe impacts on metabolic functioning (Roessig et al. 2004). As ocean warming is progressing from the surface waters downwards (IPCC 2007), shallow water fish may be affected before deeper water fish. In the Southern Ocean, krill and mackerel ice fish may therefore be affected before the deeper dwelling Patagonian toothfish. However, as juvenile Patagonian toothfish are found in shallower waters, these early life-stages may be vulnerable to increasing temperatures. Evidence suggests life stages of Antarctic fish may be particularly sensitive to changing temperatures mediating population response (Hill et al. 2005). A relationship between mackerel icefish recruitment and sea surface temperatures has been shown for stocks at South Georgia (Hill et al. 2005). Low stock sizes of mackerel icefish around the Kerguelen Islands since the mid-1990s may have been partly caused by poor recruitment and/or increased emigration due to warmer than average water temperatures (Kock & Everson 2003). As temperatures rise, Antarctic fish will disappear from banks and around oceanic islands at the northern edges of their distributions, such as the mackerel icefish from banks north of Heard Island (Kock & Everson 2003).

Even slight changes in the temperature of Antarctic waters may cause Antarctic fish to shift migratory patterns and distributional ranges (Roessig et al. 2004). Cold-water fish will shift southwards and may shift to deeper depths, although as yet there is no evidence of a marine fauna changing depth distribution in response to rising temperatures. Changing conditions in the Antarctic may also allow colonisation by temperate marine species, possibly at the expense of polar fish, as well as an increased incidence of parasites and diseases.

On a positive note, the warming of the ocean and the infusion of freshwater are likely to intensify biological activity and increase growth rates of fish (Everett & Fitzharris 1998). Ultimately, this is expected to lead to an increase in the catch of marketable fish and in the food reserve, which could offset the long-term nutrient loss resulting from reduced deep-water exchange. Even positive fisheries impacts in terms of warming may be negative with regard to the integrity of the sub-Antarctic ecosystems.

Winds, currents, MLD & stratification

The influence of warming temperatures on near-bottom hydrography of Antarctic waters and subsequent impacts on krill and commercial fish stocks are poorly understood. Coastal regions in the Southern Ocean are characteristically the most productive waters. Movement of this production offshore occurs as a result of large-

scale physical processes such as gyres, coastal currents and prevailing winds. Localised upwelling, associated with bathymetric features, can result in increased oceanic productivity as shown in the region of the Kerguelen Plateau (Moore & Abbott 2000). Predicted climate change effects in ocean properties and circulation include alterations in the carbonate chemistry (Orr et al. 2005) and a slowing down of the overturning circulation (Sloyan & Rintoul 2001). Such changes would most likely result in altered distribution patterns of key basal species (i.e. primary producers) and concomitant shifts in production, on which species such as krill and fish are reliant for food (Nicol et al., under review).

Precipitation, extreme events, and terrestrial runoff

Freshwater input from the atmosphere is unlikely to have significant impacts on krill, pelagic and demersal species in Antarctic waters. Terrestrial iron input does play a small part in driving phytoplankton dynamics in the Southern Ocean: most is released from accumulated winter snowfall when seasonal sea ice retreats (Fitch & Moore 2007). A freshening of polar waters will impact stenohaline Antarctic fish, but little information exists on salinity tolerance ranges (Roessig et al. 2004).

Sea level rise

Sea level rise is unlikely to have direct significant impacts on krill, pelagic and demersal species in Antarctic waters. Sea level rise may cause floating of the ice sheets attached to the mainland, and so may accelerate the loss of ice around Antarctica (see Sea Ice section)

Acidification (CO_2 and pH)

The impacts of ocean acidification on Southern Ocean krill, fish and other species has not been assessed. Given the projected under-saturation with regard to calcium carbonate of the entire Southern Ocean water column by the end of this century (Caldeira & Wickett 2005, Orr et al. 2005), this must be a priority area for research. The likely responses of marine organisms to a decline in pH have been assessed for a limited number of species under laboratory conditions (e.g., Kikkawa et al. 2003, Pedersen & Hansen 2003, Engel et al. 2005). Little is known of the effects of a gradual, long-term lowering of pH. As well as dissolution of carbonate (aragonite and calcite) shells and structures produced by calcifying organisms (Riebesell et al. 2000), acidification will increase physiological stress on marine fauna by influencing metabolic rates (Pörtner et al. 2004). Important metabolic processes, such as respiration in fish, may also be impaired by the acidity, as lowering the pH reduces the efficiency of oxygen exchange in their gills. Squid, an important member of the Southern Ocean ecosystem, are considered acutely sensitive to even small changes in ambient CO_2 (Pörtner et al. 2004). However, the impacts of ocean acidification are most likely to be evidenced in the alteration of plankton communities at the base of food webs. Pteropods, with their aragonite shells, dissolve rapidly in waters under-saturated with aragonite (Orr et al 2005). Pteropods are prominent components of the Southern Ocean web and also account for the majority of the annual export flux of both carbonate and organic carbon in the Southern Ocean. Populations are likely to decline in the Southern Ocean over the coming century with knock-on effects for higher trophic levels such as commercial fish and baleen whales.

Sea ice cover
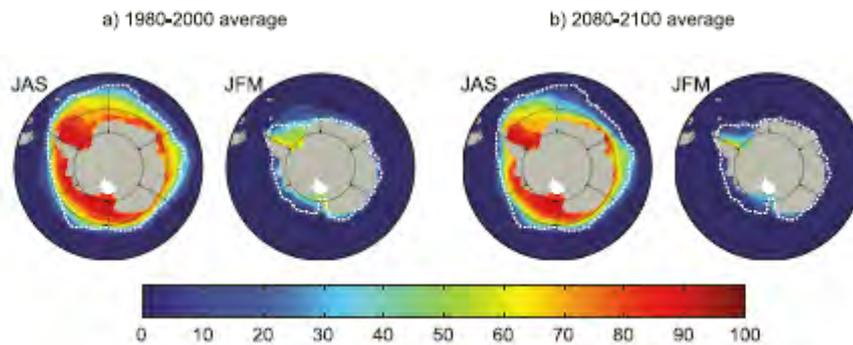
Figure 7.2 Multi-model mean sea ice concentration (%) for January to March (JFM) and June to September (JAS) in the Antarctic for the periods a) 1980-2000 and b) 2080-2100 for the SRES A1B scenario. The dashed white line indicates the present-day 15% average sea ice concentration limit. From IPCC 2007.

Climate change in Antarctica is expected to reduce the areal extent of sea-ice; this would almost certainly reduce photosynthetic carbon fixation, destroy habitats, and disrupt the life cycles of many marine animals. Marine zooplankton, such as krill, and animals at higher trophic levels, whose present-day biogeographic ranges are directly related to the extent of sea-ice coverage, might be most seriously impacted. On the other hand, increased meltwater input from the continental ice sheet might have a compensatory effect by changing water column stability and stratification, and extending the high-production zone further from shore. The seasonal retreat of sea ice is associated with large phytoplankton blooms extending over thousands of kilometres within areas of recent ice retreat (Fitch & Moore 2007).

Although it is well established that in some regions of Antarctica there is a close relationship between krill abundance and ice cover (Loeb et al. 1997; Nicol et al. 2000c); on an ocean-wide scale there are some inconsistencies if sea ice alone is seen to be the dominant factor in determining krill distribution and abundance. Krill abundance is highest in the area where sea ice extent is minimal or non-existent (Atkinson et al. 2004) and is thought to be relatively low in areas where sea ice extent is at its greatest (Nicol et al. 2000c). Correlations between sea ice and oceanic productivity hold for some areas but not for others (Constable et al. 2003). There are also suggestions that perhaps sea ice and krill abundance are both responding to either regional or temporal variations in ocean circulation patterns rather than being in a simple cause and effect relationship (Nicol et al. 2000). In areas where winter sea ice cover is minimal, such as off the Antarctic Peninsula, small year-to-year changes in ice cover may have an amplified effect on productivity, whereas in areas with considerable ice cover the effect may be much less. There may also be some interaction between the retreat of winter sea ice and the location of the shelf break where the adult krill population is centred. Krill habitat is likely to be defined by conditions that allow for the successful maintenance of adult populations as well as effective reproduction (Nicol 2006).

There is considerable uncertainty about the possible effect of future changes in the physical environment of the Southern Ocean on biological productivity. It has been suggested that a decrease in sea ice cover might actually lead to an increase in overall productivity and that changes in the balance between sea ice and open water habitats

associated with a 25% decrease in sea ice, would result in a 10% increase in overall productivity in the Southern Ocean (Arrigo & Thomas 2004). Changes in productivity might, however, be associated with shifts in phytoplankton community structure, such as has been observed off the Antarctic Peninsula where small cryptophytes have replaced larger diatoms and this may favour herbivorous species other than krill (Moline et al. 2004). Shifts between diatoms and *Phaeocystis* are more likely and potentially much more important, as noted by Arrigo et al. (1998). Such changes in species composition of the phytoplankton community can affect the entire food web structure and other changes may affect the seasonality of production which can also have wide ramifications. The model used by Arrigo & Thomas (2004) also indicated an 86% drop in the productivity in the sea ice if annual sea ice cover declined by 50%, and a 39% decline in productivity in the marginal ice zone. As these two biomes are critical to krill survival, it is likely that such a change in productivity would severely impact krill populations. Food supply in spring and summer is essential to ensure successful krill growth and reproduction, but under current environmental regimes it may well be food availability for krill larvae in winter that is the critical factor regulating the long term success of krill populations. Krill are long-lived organisms - suggested longevity is 5-7 years - and they reproduce once they have reached two years of age. Recruitment of krill in the South Atlantic has been shown to be extremely variable with peaks of successful recruitment every 4-5 years. These peaks are associated with years where ice cover is greatest and these too have a 4-5 year cycle. Thus, an individual krill might expect to encounter at least one year in its lifetime when conditions are favourable for successful reproduction. A decreased frequency of high sea ice years may have a disproportionate effect on the krill population because it could de-couple the life cycle from the scales of environmental variation (Nicol et al. in review).

Smaller growth rates of mackerel ice fish at South Georgia following warm summers may be the result of a reduction in krill and other prey availability during warmer years (North 2005). These fish are susceptible to changes in prey abundance, as evidenced in the collapse of the mackerel icefish stock around South Georgia during years of krill scarcity (Kock & Everson 2003). Fish species, such as mackerel icefish, have increased in importance in the diet of predators (such as Antarctic fur seals) in certain regions of the Southern Ocean, concurrent with the decline in krill leading to a potential increased pressure on icefish stocks (Kock & Everson 2003).

Impacts of Climate Change on Sub-Antarctic Fisheries

Socio-economic impacts

At present, Australian participation in sub-Antarctic fisheries is small, limited to one vessel operating around Macquarie Island and three vessels in the Heard and MacDonald Islands AFZ (Hender & Larcombe 2007b,c). Assuming no adverse effects on Patagonian toothfish and mackerel icefish biomass through climate change influencing trophic structure in the Southern Ocean, these fisheries may benefit from faster fish growth rates and increased regional productivity. Further, fishing seasons may be extended as global temperatures rise and sea ice cover becomes seasonal. The decline in sea ice may also allow profitable exploitation of areas presently rarely fished, such as in Australia's EEZ adjacent to the continent. However, loss of pteropod communities with ocean acidification and the decline in krill communities as sea ice declines will impact the entire Southern Ocean ecosystem and may result in a decline in commercial fish stocks.

Industry adaptation capability

The Australian sub-Antarctic fisheries are extremely well regulated and managed. The opportunity for adaptation by fishers within the management framework will depend on the policy decisions and zoning of the fishing regions. Interactions with non-target species, such as seabirds and marine mammals, are likely to influence adaptation potential, as the fisheries are managed to reduce such interactions. As populations of non-target species change abundance and distribution due to climate change, the fisheries may have to revisit trigger and reference points for bycatch species. For example, abundance and therefore interaction frequency may change in ways that do not reflect increased fishing impact, but rather, reflect changing biological patterns. Industry may have to develop new fishing strategies or gear types that target key species more efficiently, and reduce further undesirable interactions with non-target species.

Key Points: Sub-Antarctic Fisheries and Climate Change

Physical

- The Southern Ocean is projected to be under-saturated with regard to calcium carbonate through its entire water column by the end of the century.

- Sea ice is expected to decline and become more seasonal.

Biological

- Changes to krill biomass and other plankton species, associated with reduced sea ice and lowered pH may have severe consequences for exploited fish species and other predators.

- Increased water temperature may impact metabolic rates for some fished species and lead to changes in distribution for others

Socio-economic

- Additional work is needed to explore the socio-economic impacts in this region. The fisheries are well managed and tightly regulated, with good industry co-management. Adaptation potential is high given this cooperation.

---

8. Glossary

Adaptive Capacity	ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.
Advection	refers to the movement of water, or to animals or plants carried along with moving water.
Aragonite	a crystalline form of calcium carbonate laid down by marine organisms such as **pteropods** (pelagic marine snails) and reef-building corals. More soluble than **calcite** which is commonly laid down by calcifying phytoplankton.
Bathymetric	refers to the depth of the ocean. A bathymetric chart will show the depths of the sea floor
Benthic	referring to the sea floor; usually refers to fauna that lives on the seafloor, such as sponges, crabs and flatfish. Benthic species are also called **demersal** species.
Downwelling	the movement of water from the surface to depth. Downwelling can occur at the coast, or in the open ocean. Downwelling regions are typically low productivity.
EEZ	Exclusive Economic Zone. This zone typically extends offshore to a distance of 200 nm from the coast, and surrounds most countries.
ENSO	El Nino-Southern Oscillation. A set of interacting parts of a single global system of coupled ocean-atmosphere climate fluctuations. The Pacific ocean signatures, El Niño and La Niña produce large temperature fluctuations in surface waters of the tropical Pacific Ocean. ENSO is the most prominent known source of inter-annual variability in weather and climate around the world (~3 to 8 years), though not all areas are affected.
Eutrophic	environment or region where productivity is high due to high input of nutrients.
Mixed layer	upper portion of the ocean (typically 20 - 100 metres in thickness) where the wind mixes constituents (e.g. nutrients, salts) to give constant concentration within this layer and where there is relatively constant temperature with depth compared with deeper waters.
Oligotrophic	low nutrient environment or region where the lack of nutrients such as nitrate restricts biological productivity.
Ontogenetic	occurring during successive stages of an animals' life cycle.
Pelagic	living at the surface or in upper ocean waters. Pelagic species include tuna and sardines. The pelagic zone is the part of the ocean comprising the water column (i.e. all of the sea other than that near the coast or the sea floor).
Phenology	the timing of events in an animals' life, such as when it lays eggs, migrates, or hibernates. As these events may be sensitive to climate, phenological studies may provide indirect evidence of climate impacts on biology.

Phytoplankton	minute, usually single-celled, free-floating aquatic algae. Important source of organic material and energy in marine food webs. They also produce half the world's oxygen, the other half is produced by terrestrial plants.
Purse seine fishery	a fishery in which the main fishing gear is a purse seine net. This mesh net circles the fish, and then is "pursed" or closed at the base, and drawn back to the boat where the fish are brought aboard (e.g. skipjack tuna) or transferred to a cage (e.g. southern bluefin tuna).
Scenario	coupled ocean-atmosphere models are used to project or predict future changes under various scenarios. Scenarios can be very simple (e.g. CO_2 increasing at 1% per year) or more realistic (e.g. the Intergovernmental Panel on Climate Change (IPCC) SRES scenarios). Which scenarios should be considered most realistic is currently uncertain, as the projections of future CO_2 and sulfate emissions are in themselves uncertain.
Stenohaline	tolerant of a narrow range of salinity
Thermocline	depth at which the water temperature changes most rapidly, typically at the base of the mixed layer.
Trophically-linked	organisms that are linked via their diet. A fish that eats a species of zooplankton is said to be "trophically-linked".
Upwelling	movement of water from depth to the surface, usually enriching the upper waters with nutrients from the deeper waters.
Vulnerability	degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes.
Zonal	along lines of latitude (i.e. east-west direction); the opposite is meridional (i.e. north-south direction), or relative to lines of longitude (meridians).

9. References

The references are organised by each report section to allow the reader to see the appropriate literature more easily.

Introduction: Climate and Australian Fisheries and Aquaculture

ABARE 2007. Australian Fisheries Statistics, 2006. Canberra, June.

Allan R.J., Reason C.J.C., Lindesay J.A. and Ansell T.J. 2003. Protracted ENSO episodes and their impacts in the Indian Ocean region. Deep-Sea Research Part II: Topical Studies in Oceanography, 50: 2331-2347.

Baker, A. C., C. J. Starger, T. R. McClanahan and P. W. Glynn 2004. Corals' adaptive response to climate change. Nature 430: 741.

Baumgartner T.R., Soutar A. and Ferreira-Bartrina V. 1992. Reconstruction of the history of Pacific Sardine and Northern Anchovy populations over the past two millennia from sediments of the Santa Barbara Basin, California. California Cooperative Oceanic Fisheries Investigations Reports, 33: 24-40.

Bopp L., Monfray P., Aumont O., Dufresne J.-L., Le Treut H., Madec G., Terray L. and Orr J.C. 2001. Potential impact of climate change on marine export production. Global Biogeochemical Cycles, 151: 81–100.

Boyd P.W. and Doney S.C. 2002. Modeling regional responses by marine pelagic ecosystems to global climate change, Geophysical Research Letters, 29:1806, doi:10.1029/2001GL014130.

Cai W., Shi G., Cowen T., Bi D and Ribbe J. 2005. The response of the Southern Annular Mode, the East Australian Current, and the southern mid-latitude ocean circulation to global warming. Geophysical Research Letters 32, Art. No. L23706.

Chavez F.P., Ryan J., Lluch-Cota S.E. and Niquen M. 2003. From anchovies to sardines and back: multidecadal change in the Pacific Ocean. Science 299: 217-221.

Cox P.M., Betts R.A., Jones C.D., Spall S.A. and Totterdell I.J. 2000. Acceleration of global warming due to carbon cycle feedbacks in a 3D coupled model. Nature, 408: 184–187.

Cubasch U., Meehl G.A., Boer G.J., Stouffer R.J., Dix M., Noda A., Senior C.A., Raper S. and Yap K.S. 2001. Projections of future climate change, pp. 525–582 In *Climate Change 2001: The Scientific Basis*, (ed. J. T. Houghton et al.) Cambridge University Press, New York.

Denman K., Hofmann E. and Marchant H. 1996. Marine biotic responses to environmental change and feedbacks to climate, pp. 483– 516 In *Climate Change, 1995*, (ed J. T. Houghton et al.), Cambridge University Press, New York.

Finney B.P., Gregory-Eaves I., Douglas M.S.V. and Smol J.P. 2002. Fisheries productivity in the northeastern Pacific Ocean over the past 2,200 years. Nature 416: 729-733.

Gordon H.B., Rotstayn L.D., McGregor J.L., Dix M.R., Kowalczyk E.A., O'Farrell S.P., Waterman L.J., Hirst A.C., Wilson S.G., Collier M.A., Watterson I.G. and Elliott T.I. 2002. The CSIRO Mk3 Climate System Model. CSIRO Atmospheric Research Technical Paper No. 60. 130 pp.

Graham N. E. and Diaz H. F. 2001. Evidence for Intensification of North Pacific Winter Cyclones since 1948. Bulletin of the American Meteorological Society, 82: 1869-1893.

Hughes T.P., Baird A.H., Bellwood D.R., Card M., Connolly S.R., Folke C., Grosberg R., Hoegh-Guldberg O., Jackson J.B.C., Kleypas J., Lough J.M., Marshall P., Nystrom M., Palumbi S.R., Pandolfi J.M., Rosen B. & Roughgarden J. 2003. Climate change, human impacts, and the resilience of coral reefs. Science 5635: 929-933.

Kappel C.V. 2005. Losing pieces of the puzzle: threats to marine, estuarine, and diadromous species. Frontiers in Ecology and Environment 3: 275-282.

Larcombe J. and McLoughlin K. (Eds) 2007. Fishery Status Reports 2006: Status of Fish Stocks Managed by the Australian Government. Bureau of Rural Sciences, Canberra.

Miller K.A. 2007. Climate variability and tropical tuna: Management challenges for highly migratory fish stocks. Marine Policy 31: 56-70.

Oppenheimer, M., O'Neill B.C., Webster M. and Agrawala S. 2007. CLIMATE CHANGE: The Limits of Consensus. Science 317: 1505-1506.

Preston N.P., Macleod I., Rothlisberg P.C. and Long B. 1997. Environmentally sustainable aquaculture production - an Australian perspective. In: *Developing and Sustaining World Fisheries*

References

Resources: The State of Science and Management. Second World Fisheries Congress, Brisbane 1996. Vol 2: Proceedings. (Eds. D.A. Hancock, D.C. Smith, A. Grant and J.P. Beumer) pp. 471-477 (CSIRO: Melbourne).

Rahmstorf S., Cazenave A., Church J.A., Hansen J.E., Keelin R.F., Parker D.E. and Somerville R.C.J. 2007. Recent Climate Observations Compared to Projections. Science 316: 709. [DOI: 10.1126/science.1136843].

Rayns N. 2007. The Australian government's harvest strategy policy. ICES Journal of Marine Science, 64: 596–598.

Raven J., Caldeira K., Elderfield H., Hoegh-Guldberg O., Liss P., Riebesell U., Shepherd J., Turley C. and Watson A. 2005. Ocean acidification due to increasing atmospheric carbon dioxide. London: Royal Society Special Report. (ISBN 0 85403 617 2).

Sarmiento J.L., Slater R., Barber R., Bopp L., Doney S.C., Hirst A.C., Kleypas J., Matear R., Mikolajewicz U., Monfray P., Soldatov V., Spall S.A. and Stouffer R. 2004. Response of ocean ecosystems to climate warming, Global Biogeochemical Cycles, 18: doi:10.1029/2003GB002134

Stenevik E.K. and Sundby S. 2007. Impacts of climate change on commercial fish stocks in Norwegian waters. Marine Policy 31: 19-31.

Thompson D.W.J. and Solomon S. 2002. Interpretation of recent Southern Hemisphere climate change. Science 296: 895-899.

Walther G., Post E., Convey P., Menzel A., Parmesan C., Beebee T.J.C, Fromentin J., Hoegh-Guldberg O. and Bairlein F. 2002. Ecological responses to recent climate change. Nature 416: 389 – 395.

Aquaculture

ABARE 2007. Australian Fisheries Statistics 2006, Canberra, June.

Appleyard, S.A., Ward, R.D 2006. Genetic diversity and effective population size in mass selection lines of Pacific oyster (*Crassostrea gigas*). Aquaculture 254: 148-159

Barlow S.M. 2002. The world market overview of fish meal and fish oil. http://www.iffo.org.uk/tech/alaska.htm (accessed December 2005).

Benemann J.R. 1992. Microalgae aquaculture feeds. Journal of Applied Phycology 4: 233-245.

Berge J.A., Bjerkeng B., Pettersen O., Schaanning M.T. and Oxnevad S. 2006. Effects of increased sea water concentrations of CO_2 on growth of the bivalve *Mytilus edulis* L. Chemosphere 62, 681-687.

Borowitzka M.A. 2007. Microalgae for aquaculture: Opportunities and constraints. Journal of Applied Phycology 9: 393-401.

Chisti Y. 2007. Biodiesel from microalgae. Biotechnology Advances 25: 294-306.

De Morais M.G. and Costa J.A.V. 2007. Isolation and selection of microalgae from coal fired power plant for biofixation of carbon dioxide. Energy Conservation and Management 48: 2169-2163.

Elliott N.G. and Reilly A. 2003. Likelihood of bottleneck event in the history of the Australian population of Atlantic salmon (*Salmo salar* L.) Aquaculture 215: 31-44.

FAO 2006. State of World Aquaculture 2006. FAO Fisheries Technical Paper. No. 500. Rome, FAO. 134p.

Gazeau F., Quiblier C., Jansen J.M., Gattuso J-P., Middelburg J.J. and Heip C.H.R. 2007. Impact of elevated CO_2 on shellfish calcification. Geophysical Research Letters 34, Art L07603, doi:10.1029/2006GL028554.

Goggin C.L. and Lester R.J.G. 1995. *Perkinsus*, a protistan parasite of abalone in Australia - a review. Marine and Freshwater Research 46, 639-646.

Harvell C.D., Mitchell C.E., Ward J.R., Altizer S., Dobson A.P., Ostfeld R.S. and Samuel M.D. 2002. Climate warming and disease risks for terrestrial and marine biota. Science 296: 2158-2162.

Hennessy K., Fitzharris B., Bates C., Harvey N., Howden S.M., Hughes L., Salinger J. and Warrick R. 2007: Australia and New Zealand. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (Eds.), Cambridge University Press, Cambridge, UK. 507-540.

Jackson C.J. and Wang Y-G. 1998. Modelling growth rate of *Penaeus monodon* Fabricus in intensively managed ponds: effects of temperature, pond age and stocking density. Aquaculture Research 29: 27-36.

Jackson C.J., Preston N.P., Burford M.A. and Thompson P. 2003. Managing the development of sustainable shrimp farming in Australia: the role of sedimentation ponds in treatment of farm discharge water. Aquaculture 226: 23-34.

Kaddam K.L. 1997. Power plant flue gas as a source of CO_2 for microalgae cultivation: economic impact of different process options. Energy Conversion and Management 38: 505-510.

Kikkawa T., Ishimatsu A. and Kita J. 2003. Acute CO_2 tolerance during the early developmental stages of four marine teleosts. Environmental Toxicology 18: 375-382.

Larcombe J., Charalambou C., Herreńa E., Casey A.M. and Hobsbawn P. 2006 *Marine Matters National Atlas of Australian Marine Fishing and Coastal Communities.* Bureau of Rural Sciences, Canberra.

Loosanoff V.L. and Tommers F.D. 1948. Effects of suspended silt and other substances on rate of feeding of oysters. Science 107: 69-70.

Michaelidis B., Ouzounis C., Paleras A. and Pörtner H.O. 2005. Effects of long-term moderate hypercapnia on acid-base balance and growth rate in marine mussels *Mytilus galloprovincialis*. Marine Ecology Progress Series 293: 109-118.

Nell J.A. 1993. Farming the Sydney Rock Oyster (*Saccostrea commercialis*) in Australia. Reviews in Fisheries Science 1: 97-120.

Pittock B (ed) 2003. *Climate Change: an Australian guide to the science and potential impacts*. Canberra, ACT: Australian Greenhouse Office 2003.

Pörtner H.O., Langenbuch M. & Reipschläger A. 2004. Biological impact of elevated ocean CO_2 concentrations: Lessons from animal physiology and earth history. Journal of Oceanography 60: 705-718.

Preston N.P., Crocos P.J., Keys S.J, Coman G.J. and Koenig R. 2004. Comparative growth of selected and non-selected Kuruma shrimp *Penaeus (Marsupenaeus) japonicus* in commercial farm ponds. Aquaculture 231: 73-82.

Preston N.P., Crocos P., Jackson C., Duncan P., Zipf M. and Koenig R. 2001a. Farming the Kuruma shrimp (*Marsupenaeus japonicus*) in Australia – A Case History. In: *The New Wave, Proceedings of the Special Session on Sustainable Shrimp Culture, Aquaculture 2001* (eds) C.L. Browdy and D.E. Jory. The World Aquaculture Society, Baton Rouge, LA, USA.

Preston N.P., Jackson C.J., Thompson P., Austin M., Burford M.A. and Rothlisberg P.C. 2001b. Prawn farm effluent: Composition, origin and treatment. Fisheries Research and Development Corporation, Australia, Final Report, Project No. 95/162

Preston N.P., Macleod I., Rothlisberg P.C. and Long B. 1997. Environmentally sustainable aquaculture production - an Australian perspective. In: *Developing and Sustaining World Fisheries Resources: The State of Science and Management. Second World Fisheries Congress, Brisbane 1996. Vol 2: Proceedings.* (Eds. D.A. Hancock, D.C. Smith, A. Grant and J.P. Beumer) pp. 471-477 (CSIRO: Melbourne).

Ryan J. 2004. Farming the Deep Blue. A report prepared by Bord Iascaigh Mhara-Irish Sea Fisheries Board and Irish Marine Institute. Presented at ''Farming the Deep Blue,'' Limerick, Ireland, October 6–7, 2004.

Shepherd S.A. and Lawas H.M. 1974. Studies on southern Australian abalone (genus Haliotis). 2. reproduction of five species. Australian Journal of Marine and Freshwater Research 25: 47-62.

Spolaore P., Joannis-Cassan C., Duran E. and Isambert A. 2006. Commercial applications of microalgae. Journal of Bioscience and Bioengineering 101: 87-96.

Vilchis L.I., Tegner M.J., Moore J.D., Friedman J.D., Friedman C.S., Riser K.L., Robbins T.T. and Dayton P.K. 2005. Ocean warming effects on growth reproduction and survivorship of southern California abalone. Ecological Applications 15:469-480.

Northern Fisheries

ABARE 2007. Australian Fisheries Statistics 2006, Canberra, June.

Bensley., N. 2007. Torres Strait Lobster Fishery, pp. 57–64. In: Larcombe, J. and McLoughlin, K. (eds.) (2007) *Fishery Status Reports 2006: Status of Fish Stocks Managed by the Australian Government*. Bureau of Rural Sciences, Canberra.

Berge, J.A., Bjerkeng, B., Pettersen, O., Schaanning, M.T. & Oxnevad, S. 2006. Effects of increased sea water concentrations of CO_2 on growth of the bivalve *Mytilus edulis* L. *Chemosphere* 62, 681-687.

Blaber S.J.M. 2000. Tropical Estuarine Fishes: Ecology, Exploitation and Conservation. Blackwell Science, Oxford.

BOM. 2004. Queensland climate change and community vulnerability to tropical cyclones. Bureau of Meteorology, Australian Government.

Brewer D.T., Rawlinson N., Eayrs S. and Burridge C.Y. 1998. An assessment of Bycatch Reduction Devices in a tropical Australian prawn trawl fishery. Fisheries Research 36: 195-215.

References

Catchpole A. and Auliciems A. 1999. Southern oscillation and the northern Australian prawn catch. International Journal of Biometeorology 43: 110-112.

Caton A. and McLoughlin K. 2004. Overview. Pages 1-24 In A. Caton and K. McLaughlin, editors. *Fishery Status Reports 2004: Status of Fish Stocks Managed by the Australian Government.* Bureau of Rural Sciences, Canberra.

Coles R.G., Long W.J.L., Watson R.A. and Derbyshire K.J. 1993. Distribution of seagrasses, and their fish and penaeid prawn communities, in Cairns Harbor, a tropical estuary, northern Queensland, Australia. Australian Journal of Marine and Freshwater Research 44: 193-210.

CSIRO 1993. Recruitment processes in commercially important prawn species and causes of declines in stocks of commercially important prawns in the northern prawn fishery. CSIRO Division of Fisheries, Cleveland Marine Laboratory, Australia. Final Report FRDC Project 85/85 and 89/13.

CSIRO 1996. Interim marine bioregionialisation for Australia: towards a national system of marine protected areas. CSIRO Division of Fisheries and CSIRO Division of Oceanography. Final Report to Ocean Rescue 2000 and ERIN, Canberra.

Dall W. 1981. Osmoregulatory ability and juvenile habitat preference in some penaeid prawns. Journal of Experimental Marine Biology and Ecology 54: 55-64.

Dall W., Hill B.J., Rothlisberg P.C. and Staples D.J. 1990. The Biology of the Penaeidae. Academic Press 489 pp.

DEH 2004. Assessment of the ecological sustainability of management arrangements for the Northern Territory Finfish Trawl Fishery. Australian Government, Department of the Environment and Heritage, Canberra.

Ellison J.C. & Stoddart D.R. 1991. Mangrove ecosystem collapse during predicted sea-level rise – holocene analogs and implications. Journal of Coastal Research 7: 151-165.

Evans C.R., Opnai L.J. and Kare B.D. 1997. Fishery ecology and oceanography of the prawn *Penaeus merguiensis* (de Man) in the Gulf of Papua: Estimation of maximum sustainable yield and modelling of yield, effort and rainfall. Marine and Freshwater Research 48: 219-228.

Hall M.O., Durako M.J., Fourqurean J.W. and Zieman J.C. 1999. Decadal changes in seagrass distribution and abundance in Florida Bay. Estuaries 22: 445-459.

Haywood M.D.E. and Staples D.J. 1993. Field estimates of growth and mortality of juvenile banana prawns (*Penaeus merguiensis*). Marine Biology 116: 407-416.

Haywood M.D.E., Vance D.J. and Loneragan N.R. 1995. Seagrass and algal beds as nursery habitats for tiger prawns (*Penaeus semisulcatus* and *P. esculentus*) in a tropical Australian estuary. Marine Biology 122: 213-223.

Hennessy K., Page C., McInnes K., Walsh K., Pittock B., Bathols J. and Suppiah R. 2004. Climate change in the Northern Territory. Consultancy report for the Northern Territory Department of Infrastructure, Planning and Environment. CSIRO Atmospheric Research.

Henry G.W. & Lyle J.M. (eds.) 2003. National Recreational Fishing Survey. In *The National Recreational and Indigenous Fishing Survey*. Canberra: Australian Government Department of Agriculture, Fisheries and Forestry, FRDC Project No. 99/158, 27-97.

Hill B.J., Haywood M., Venables W., Gordon S.R., Condie S., Ellis N.R., Tyre A., Vance D., Dunn J., Mansbridge J., Moseneder C., Bustamante R. and Pantus F. 2002. Surrogates I - Predictors, impacts, management and conservation of the benthic biodiversity of the Northern Prawn Fishery. Final report on FRDC Project 2000/160. CSIRO, Cleveland.

Hughes L. 2003. Climate change and Australia: Trends, projections and impacts. Austral Ecology 28: 423-443.

IOC 1989. Second IOC-FAO workshop on recruitment of penaeid prawns in the Indo-West Pacific region (PREP). Intergovernmental Oceanographic Commission Workshop Report No. 64, Phuket, Thailand, 25-31 September 1989.

Jackson C.J. and. Burford M.A. 2003. The effects of temperature and salinity on growth and survival of larval shrimp *Penaeus semisulcatus* (Decapoda : Penaeoidea). Journal of Crustacean Biology 23: 819-826.

Jackson C.J., Rothlisberg P.C. and Pendrey R.C. 2001. Role of larval distribution and abundance in overall life-history dynamics: a study of the prawn *Penaeus semisulcatus* in Albatross Bay, Gulf of Carpentaria, Australia. Marine Ecology Progress Series 213: 241-252.

Kappel C.V. 2005. Losing pieces of the puzzle: threats to marine, estuarine and diadromous species. Frontiers in Ecology and the Environment 3: 275-282.

Kenyon R., Burridge C., Poiner I. and Hopkins E. 1999. Impact of the McArthur River project mine transhipment facility on the marine environment. Final Report by CSIRO to McArthur River Mining Pty Ltd.

References

Kurihara, H., Shimode, S. & Shirayama, Y. 2004. Sub-lethal effects of elevated concentration of CO_2 on planktonic copepods and sea urchins. Journal of Oceanography 60, 743-750.

Lee S.Y. 2004. Relationship between mangrove abundance and tropical prawn production: a re-evaluation. Marine Biology 145: 943-949.

Loneragan N.R., Adnan N.A., Connolly R.M. & Manson F.J. 2005. Prawn landings and their relationship with the extent of mangroves and shallow waters in western peninsular Malaysia. Estuarine, Coastal and Shelf Science 63: 187-200.

Loneragan, N.R. and Bunn S.E. 1999. River flows and estuarine ecosystems: Implications for coastal fisheries from a review and a case study of the Logan River, southeast Queensland. Australian Journal of Ecology 24: 431-440.

Loneragan N.R., Crocos P.J., Barnard R.M., McCulloch R.R., Penn J.W., Ward R.D. and Rothlisberg P.C. 2004. An approach to evaluating the potential for stock enhancement of brown tiger prawns (*Penaeus esculentus* Haswell) in Exmouth Gulf, Western Australia. Pages 444-464 In K.M. Leber, S. Kitada, H.L. Blankenship and T. Svasand, editors. *Stock Enhancement and Sea Ranching,* 2nd Edition: Development, Pitfalls and Opportunities. Blackwell Science Ltd./Fishing News Books, Oxford.

Loneragan N.R., Kenyon R.A., Haywood M.D.E. and Staples D.J. 1994. Population dynamics of juvenile tiger prawns (*Penaeus esculentus* and *P. semisulcatus*) in seagrass habitats of the western Gulf of Carpentaria, Australia. Marine Biology 119: 133-143.

Loneragan N.R., Kenyon R.A., Staples D.J., Poiner I.R. and Conacher C.A. 1998. The influence of seagrass type on the distribution and abundance of postlarval and juvenile tiger prawns (*Penaeus esculentus* and *P. semisulcatus*) in the western Gulf of Carpentaria, Australia. Journal of Experimental Marine Biology and Ecology 228: 175-195.

Love G. 1987. Banana prawns and the Southern Oscillation Index. Australian Meteorological Magazine 35: 47-49.

Manson F.J., Loneragan N.R., Harch B.D., Skilleter G.A. & Williams L. 2005. A broad-scale analysis of links between coastal fisheries production and mangrove extent: a case-study for northeastern Australia. Fisheries Research 74: 69-85.

Meager J.J., Vance D.J., Loneragan N.R. and Williamson I. 2003. Seasonal variation and environmental influences on juvenile banana prawn (*Penaeus merguiensis*) abundance in a subtropical estuary (Logan River) of eastern Australia. Estuarine Coastal and Shelf Science 57: 569-576.

Michaelidis B., Ouzounis C., Paleras A. and Pörtner H.O. 2005. Effects of long-term moderate hypercapnia on acid-base balance and growth rate in marine mussels *Mytilus galloprovincialis*. Marine Ecology Progress Series 293: 109-118.

Milton D., Yarrao M. Fry G.and Tenakanai C. 2005. Response of barramundi *Lates calcarifer* populations in the Fly River, Papua New Guinea to mining, fishing and climate-related perturbation. Marine and Freshwater Research 56: 969-981.

O'Brien C J 1994. The effects of temperature and salinity on growth and survival of juvenile tiger prawns *Penaeus esculentus* (Haswell). Journal of Experimental Marine Biology and Ecology 183: 133-145.

Pender P.J., Willing R.S. and Ramm D.C. 1992. Northern prawn fishery bycatch study: Distribution, abundance, size and use of bycatch from the mixed species fishery. Pages 1-70 In *Northern Territory*, Department of Primary Industry and Fisheries, Fishery Report 26.

Penn J.W. and Caputi N. 1985. Stock recruitment relationships for tiger prawn (*Penaeus esculentus*) fishery in Exmouth Gulf, Western Australia and their implications for management. Pages 165-173 In P.C. Rothlisberg, B.J. Hill and D.J. Staples, editors. *Second Australian National Prawn Seminar*. NPS2: Cleveland, Queensland.

Penn J.W. and Caputi N. 1986. Spawning stock recruitment relationships and environmental influences on the tiger prawn (*Penaeus esculentus*) fishery in Exmouth Gulf, Western Australia. Australian Journal of Marine and Freshwater Research 37: 491-505.

Pittock B. (ed) 2003. Climate change: An Australian guide to the science and potential impacts. Australian Greenhouse Office, Commonwealth of Australia, Canberra.

Poiner I., Conacher C., Loneragan N., Kenyon R. and Somers I.F. 1993. Effects of cyclones on seagrass communities and penaeid prawn stocks of the Gulf of Carpentaria. Final report, FRDC Projects 87/16 and 91/45. CSIRO Marine Laboratories Report. CSIRO Division of Fisheries, Cleveland, Queensland.

Poiner I., Walker D.I. and Coles R.G. 1989. Regional studies—seagrasses of tropical Australia. In L. A.W.D., A.J. McComb and S.A. Shepherd, editors. T*he biology of seagrasses: an Australian perspective*. Elsevier, Amsterdam.

References

Pörtner H.O., Langenbuch M. & Reipschläger A. 2004. Biological impact of elevated ocean CO_2 concentrations: Lessons from animal physiology and earth history. Journal of Oceanography 60: 705-718.

Raven J., Caldeira K., Elderfield H., Hoegh-Guldberg O., Liss P., Riebesell U., Shepherd J., Turley C. and Watson A. 2005. Ocean acidification due to increasing atmospheric carbon dioxide. London: Royal Society Special Report. (ISBN 0 85403 617 2).

Robins J.B., Halliday I.A., Staunton-Smith J., Mayer D.G. and Sellin M.J. 2005. Freshwater-flow requirements of estuarine fisheries in tropical Australia: a review of the state of knowledge and application of a suggested approach. Marine and Freshwater Research 56: 343-360.

Rothlisberg, P., Staples D., Poiner I. and Wolanski E. 1988. The possible impact of the greenhouse effect on commercial prawn populations in the Gulf of Carpentaria. In *Greenhouse: Planning for Climate Change*. CSIRO Publications, East Melbourne, Victoria, Australia.

Rothlisberg P.C., Church J.A. and Forbes A.M.G. 1983. Modelling the advection of vertically migrating shrimp larvae. Journal of Marine Research 41: 511-538.

Sheaves M. 1998. Spatial patterns in estuarine fish faunas in tropical Queensland: a reflection of interaction between long-term physical and biological processes? Marine and Freshwater Research 49: 31-41.

Staples D.J. 1980. Ecology of juvenile and adolescent banana prawns, *Penaeus merguiensis*, in a mangrove estuary and adjacent off-shore area of the Gulf of Carpentaria. 1. Immigration and settlement of postlarvae. Australian Journal of Marine and Freshwater Research 31: 635-652.

Staples D.J. and Heales D.S. 1991. Temperature and salinity optima for growth and survival of juvenile banana prawns *Penaeus merguiensis*. Journal of Experimental Marine Biology and Ecology 154: 251-274.

Staples D.J., Vance D.J. and Loneragan N.R. 1995. Penaeid prawn recruitment variability: Effect of the environment. Pages 41-50 In *Proceedings of the Workshop on Stock-Recruitment Relationships (SRRs) in Australian Crustacean Fisheries*. Queensland Department of Primary Industry, Southern Fisheries Centre, Deception Bay, Queensland.

Staples D.J. and Vance D.J. 1987. Comparative recruitment of the banana prawn, *Penaeus merguiensis*, in 5 estuaries of the southeastern Gulf of Carpentaria, Australia. Australian Journal of Marine and Freshwater Research 38: 29-45.

Staples D.J. and Vance D.J. 1986. Emigration of juvenile banana prawns *Penaeus merguiensis* from a mangrove estuary and recruitment to offshore areas in the wet-dry tropics of the Gulf of Carpentaria, Australia. Marine Ecology Progress Series 27: 239-252.

Staunton-Smith J., Robins J.B., Mayer D.G., Sellin M.J. and Halliday I.A. 2004. Does the quantity and timing of fresh water flowing into a dry tropical estuary affect year-class strength of barramundi (*Lates calcarifer*)? Marine and Freshwater Research 55: 787-797.

Stobutzki I. and McLoughlin K. 2007 Northern Prawn Fishery, pp. 35–48. In Larcombe, J. and McLoughlin, K. (eds.) *Fishery Status Reports 2006: Status of Fish Stocks Managed by the Australian Government*. Bureau of Rural Sciences, Canberra.

Stobutzki I., Blaber S., Brewer D., Fry G., Heales D., Miller M., Milton D., Salini J., van der Velde T. and Wassenberg T. 2000. Ecological sustainability of bycatch and biodiversity in prawn trawl fisheries. Final Report 96/257 to Fisheries Development Corporation.

Vance D.J., Bishop J., Dichmont C., Hall N., McInnes K. and Taylor B. 2003. Management of common banana prawn stocks of the Gulf of Carpentaria: separating the effects of fishing from those of the environment. CSIRO Marine Research. AFMA Final Report, Project No: 98/0716.

Vance D.J., Haywood M.D.E., Heales D.S., Kenyon R.A. and Loneragan N.R. 1998. Seasonal and annual variation in abundance of postlarval and juvenile banana prawns *Penaeus merguiensis* and environmental variation in two estuaries in tropical northeastern Australia: a six year study. Marine Ecology Progress Series 163:21-36.

Vance D.J., Haywood M.D.E. and Staples D.J. 1990. Use of a mangrove estuary as a nursery area by postlarval and juvenile banana prawns, *Penaeus merguiensis* Deman, in Northern Australia. Estuarine Coastal and Shelf Science 31: 689-701.

Vance D.J., Staples D.J. and Karr J.D. 1985. Factors affecting year-to-year variation in the catch of banana prawns (*Penaeus merguiensis*) in the Gulf of Carpentaria. Journal of International Exploration of the Sea 42: 83-97.

Walsh K., Cai W., Hennessy K., Jones R., McInnes K., Nguyen K. and Page C. 2002. Climate change in Queensland under enhanced greenhouse conditions. Final Report 1997-2002. Report on research undertaken for Queensland Departments of State Development, Main Roads, Health, Transport, Mines and Energy, Treasury, Public Works, Primary Industries and Natural Resources. CSIRO Atmospheric Research.

References

Walther G., Post E., Convey P., Menzel A., Parmesan C., Beebee T.J.C., Fromentin J., Hoegh-Guldberg O. and Bairlein F. 2002. Ecological responses to recent climate change. Nature 416: 389-395

Watson R.A., Coles R.G. and Long W.J.L. 1993. Simulation estimates of annual yield and landed value for commercial penaeid prawns from a tropical seagrass habitat, northern Queensland, Australia. Australian Journal of Marine and Freshwater Research 44: 211-219.

South-East Demersal Fisheries

ABARE 2007. Australian Fisheries Statistics, 2006. Canberra, June.

Ajani P. Hallegraeff G.M. and Pritchard T. 2001. Historic overview of algal blooms in marine and estuarine waters of New South Wales, Australia. Proceedings of the Linnean Society of New South Wales 123: 1-22.

Bell J.D., Quartarro N. and Henry G.W. 1991. Growth of snapper, *Pagrus auratus*, from south-eastern Australia in captivity. New Zealand Journal of Marine and Freshwater Research 25: 117-121.

Brodeur R.D., Ralston S., Emmett R.L., Trudel M., Auth T.D. and Phillips A.J. 2006. Anomolous pelagic nekton abundance, distribution, and apparent recruitment in the northern California Current in 2004 and 2005. Geophysical Research Letters 33, Art No. L22S08.

Cai W., Shi G., Cowen T., Bi D and Ribbe J. 2005. The response of the Southern Annular Mode, the East Australian Current, and the southern mid-latitude ocean circulation to global warming. Geophysical Research Letters 32, Art. No. L23706.

Caton A. and MacLoughlin K. 2004. Fishery status Reports 2004. Australian Government Bureau of Resource Sciences, Canberra, ACT, Australia.

Davenport S. and Bax N. 2002. A trophic study of a marine ecosystem off south eastern Australia using stable isotopes of carbon and nitrogen. Canadian Journal of Fisheries and Aquatic Sciences 51: 514-530.

Dela-Cruz J., Ajani P., Lee R., Pritchard T. and Suthers I. 2002. Temporal abundance patterns of the red tide dinoflagellate *Noctiluca scintillans* along the southeast coast of Australia. Marine Ecology Progress Series 236: 75-88.

Dela-Cruz J., Middleton J.H. and Suthers I.M. 2003. Population growth and transport of the red tide dinoflagellate, *Noctiluca scintillans*, in the coastal waters off Sydney Australia, using cell diameter as a tracer. Limnology and Oceanography 48: 656-674.

Edgar G.J. 1997. *Australian Marine Life*. Reed. Kew, Victoria.

Edyvane K.S. 2003. Conservation, monitoring and recovery of threatened giant kelp (*Macrocystis pyrifera*) beds in Tasmania. Final Report for Environment Australia. Department of Primary Industries, Water and Environment, Hobart, Tasmania.

Evans K., Thresher R.E., Warneke R.M., Bradshaw C.J.A., Pook M., Thiele D. and Hindell M.A. 2005. Periodic variability in cetacean strandings: links to large-scale climate events. Biology Letters 1: 147-150.

Gardner N., Kwa C. and Paturusi A. 1994. First recording of the European shore crab *Carcinus maenas* in Tasmania. Tasmanian Naturalist 116: 26-28.

Gillett N.P. and Thompson D.W. 2003. Simulation of recent southern hemisphere climate change. Science 302: 273-275.

Harris G.P., Davies P., Nunez M. & Meyers G. 1988. Interannual variability in climate and fisheries in Tasmania. Nature 333: 754-757

Jenkins J.P. 2005. Influence of climate on the fishery recruitment of a temperate, seagrass-associated fish, the King George whiting *Sillaginoides punctata*. Marine Ecology Progress Series 288: 263-271.

Johnson C.R., Ling S., Ross J., Shepherd S.A and Miller K. 2005. Range extension of the long-spined sea urchin (*Centrostephanous rodgersii*) in eastern Tasmania: Assessment of potential threats to fisheries. FRDC Final Report 2001/044, School of Zoology, University of Tasmania.

Jones J.M. and Widman M. 2004. Early peak in Antarctic oscillation index. Nature 432: 290-291.

Larcombe J. and McLoughlin K. (Eds) 2007. Fishery Status Reports 2006: Status of Fish Stocks Managed by the Australian Government. Bureau of Rural Sciences, Canberra.

Lyne V., Thresher R. and Rintoul S. 2005. Regional impacts of climate change and variability in south-east Australia: Report of a joint review by CSIRO Marine Research and CSIRO Atmospheric Research. CSIRO Internal Report, Hobart, TAS.

Parmesan C. and Yohe G. 2003. A globally coherent fingerprint of climate change impacts across natural systems. Nature 421: 37-42.

Perry A.L., Low P.J., Ellis J.R. and Reynolds J.D. 2005. Climate change and distribution shifts in marine fishes. Science 308: 1912-1915.

References

Poloczanska E.S., Babcock R.C., Butler A., Hobday A.J., Hoegh-Guldberg O., Kunz T.J., Matear R., Milton D., Okey T.A. and Richardson A.J. 2007. Climate Change and Australian Marine Life. Oceanography and Marine Biology Annual Review 45: 409-480.

Ridgway K.R. 2007. Long-term trend and decadal variability of the southward penetration of the East Australian Current. Geophysical Research Letters 34: L13613, doi:10.1029/2007GL030393.

Smith A.D.M. and Smith D.C. 2001. A complex quota-managed fishery: science and management in Australia's South-east Fishery. Introduction and Overview. Marine and Freshwater Research 52: 353-360.

Thresher R.E., Harris G.P., Gunn J.S. and Clementson L.A. 1989. Planktonic production pulses and episodic settlement of a temperate marine fish. Nature 341: 641-642.

Thresher R.E., Nichols P.D., Gunn J.S., Bruce B.D. and. Furlani D.M. 1992. Evidence for microbial production based on seagrass detritus supporting a planktonic food chain. Limnology and Oceanography 37: 1754-1758.

Thresher R.E. 1994. Climatic cycles may help explain fish recruitment in south east Australia. Australian Fisheries 53: 20-22.

Thresher R.E., Proctor C.H., Gunn J.S. and Harrowfield I.R. 1994. An evaluation of electron-probe microanalysis of otoliths for stock delineation and identification of nursery areas in a southern temperate groundfish, *Nemadactylus macropterus* (Cheilodactylidae). Fishery Bulletin (U.S.) 92: 817-840.

Thresher R.E. 2002. Solar correlates of southern hemisphere climate variability. International Journal of Climatology 22: 901-915.

Thresher R.E., Proctor C., Ruiz R., Gurney R., MacKinnon C., Walton W., Rodriguez L. and N. Bax. 2003. Invasion dynamics of the European green crab, *Carcinus maenas*, in Australia. Marine Biology 142: 867-876.

Thresher R.E., Rintoul S.R., Koslow J.A., Weidman C., Adkins J. and Proctor C. 2004. Oceanic evidence of climate change in southern Australia over the last three centuries. Geophysical Research Letters 31:L07212.

Thresher R.E., Koslow A.J., Morison A.K. and Smith D.C. 2007. Depth-mediated reversal of the effects of climate change on long-term growth rates of exploited marine fish. Proceedings of the National Academy of Science (U.S.) 104: 7461-7465.

Walton W.C., MacKinnon C., Rodriguez L.F., Proctor C. and Ruiz G.M. 2002. Effect of an invasive crab on a marine fishery: green crab, *Carcinus maenas*, predation upon a venerid clam, *Katelysia scalarina*, in Tasmania (Australia). Journal of Experimental Marine Biology and Ecology 272: 171-189.

Williams H. and Schaap A.H. 1992. Preliminary results of a study into the incidental mortality of sharks in gillnets in two Tasmanian shark nursery areas. Australian Journal of Marine and Freshwater Research 43: 237-250.

Western Fisheries

ABARE 2007. Australian Fisheries Statistics, 2006. Canberra, June.

Caputi N., Brown R.S. and Chubb C.F. 1995. Regional prediction of the western rock lobster, *Panulirus cygnus*, commercial catch in Western Australia, Crustaceana 68: 245-256.

Caputi N., Fletcher W., Pearce A. and Chubb C. 1996. Effect of the Leeuwin Current on the recruitment of fish and invertebrates along the Western Australian coast. Marine and Freshwater Research 47: 147-155.

Caputi, N., Chubb C. and Pearce A. 2001. Environmental effects on recruitment of the western rock lobster, *Panulirus cygnus*. Marine and Freshwater Research 52: 1167-1174.

Caputi N., Chubb C., Melville-Smith R., Pearce A.F. and Griffin D.A. 2003. Review of the relationships between life history stages of the western rock lobster, *Panulirus cygnus*, in Western Australia. Fisheries Research 65: 47-61.

Fisheries Management Paper 126. The south coast estuarine fishery. Available at www.fish.wa.gov.au/docs/mp/mp126/fmp126.pdf

Fletcher W.J. and Head F. (eds) 2006. *State of the Fisheries Report 2005/06*. Department of Fisheries, Western Australia.

Griffin D., Wilkin J., Chubb C., Pearce A. and Caputi N. 2001a. Ocean currents and the larval phase of Australian western rock lobster, *Panulirus cygnus*. Marine and Freshwater Research 52: 1187-1200.

Griffin D., Wilkin J., Chubb C., Pearce A. and Caputi N. 2001b. Mesoscale oceanographic data analysis and data assimilative modeling with application to Western Australian fisheries, FRDC Report 1997/139 CSIRO Marine Research, Hobart, Tasmania.

Hart A., Skepper C. and Joll L. 1999. Growth of pearl oysters in the southern and northern areas of the pearl oyster fishery and examination of environmental influences on recruitment to pearl oyster stocks. FRDC Report 95/41, Fisheries Western Australia.

Larcombe J. and McLoughlin K. (Eds) 2007. Fishery Status Reports 2006: Status of Fish Stocks Managed by the Australian Government. Bureau of Rural Sciences, Canberra.

Lenanton R.C.J., Robertson A.I. and Hansen J.A. 1982. Nearshore accumulations of detached macrophytes as nursery areas for fish. Marine Ecology Progress Series 9: 51-57.

Lenanton R.C., Joll L.M., Penn J.W. and Jones K. 1991. The influence of the Leeuwin Current on the coastal fisheries of Western Australia. Journal of the Royal Society of Western Australia 74: 101-114.

Liddy G.C., Phillips B.F. and Maguire G.B. 2004. Effects of temperature and food density on survival and growth of early stage phyllosoma of the western rock lobster, *Panulirus cygnus*. Aquaculture, 242: 207–215.

Pearce A.F. and Phillips B.F. 1988. ENSO events, the Leeuwin Current, and larval recruitment of the western rock lobster. Journal du Conseil International pour I'Exploration de la Mer. 45: 13-21.

Pearce A.F. and Caputi N. 1994. Effects of seasonal and interannual variability of the ocean environment of recruitment to the fisheries of Western Australia, FRDC Final Report 1994/032.

Penn J.W. and Caputi N. 1986. Spawning stock-recruitment relationships and environmental influences on the tiger prawn (*Penaeus esculentus*) fishery in Exmouth Gulf, Western Australia. Australian Journal of Marine and Freshwater Research 37: 491-505.

Penn J.W., Watson R.A., Caputi N. and Hall N. 1997. Protecting vulnerable stocks in multi-species prawn fisheries. In: D.A. Hancock, D.C. Smith, A. Grant and J.P. Beumer (eds). Developing and Sustaining World Fisheries Resources, The State of Science and Management, 2nd World Fisheries Congress proceedings, Brisbane, Australia. July 1996, pp. 122-129.

Penn J.W., Fletcher W.J. and Head F. (eds) 2005. State of the Fisheries Report 2003/04. Department of Fisheries, Western Australia.

Pelagic Fisheries

ABARE 2007. Australian Fisheries Statistics, 2006. Canberra, June.

Andrade H.A. and Garcia C.A.E. 1999. Skipjack tuna fishery in relation to sea surface temperature off the southern Brazilian coast. Fisheries Oceanography 8: 245-254.

Brown A. 2005. Age and growth of jack mackerel off the east coast of Tasmania. Honours Thesis, School of Zoology, University of Tasmania.

Bertrand A., Josse E., Bach P., Gros P. and Dagorn L. 2002. Hydrological and trophic characteristics of tuna habitat: consequences on tuna distribution and longline catchability. Canadian Journal of Fisheries and Aquatic Sciences 59: 1002-1013.

Brown A. 2005. Age and growth of jack mackerel off the east coast of Tasmania. Honours Thesis, School of Zoology, University of Tasmania.

Bunce A. 2004. Do dietary changes of Australasian gannets (*Morus serrator*) reflect variability in pelagic fish stocks? Wildlife Research 31: 383-387.

Campbell R.A. 1999. Long term trends in yellowfin tuna abundance in the south-west Pacific: with an emphasis on the eastern Australian Fishing Zone. Final report to the Australian Fisheries Management Authority, Canberra, 105pp.

Chavez, F.P., Ryan J., Lluch-Cota S.E. and Niquen M. 2003. From anchovies to sardines and back: multidecadal change in the Pacific Ocean. Science 299: 217-221.

Cowling A., Hobday A.J. and Gunn J. 2003. Development of a fishery-independent index of abundance for juvenile southern bluefin tuna and improvement of the index through integration of environmental, archival tag and aerial survey data. FRDC Final Report 1999/118. CSIRO Marine Research.

Cury P., Bakun A., Crawford R.J.M., Jarre A., Quiñones R.A, Shannon L.J. and Verheye H.M. 2000. Small pelagics in upwelling systems: patterns of interaction and structural changes in "wasp-waist" ecosystems. ICES Journal of Marine Science 57: 603-618.

Dimmlich W.F., Breed W.G., Geddes M. and Ward T.M. 2004. Relative importance of gulf and shelf waters for spawning and recruitment of Australian anchovy, *Engraulis australis*, in South Australia. Fisheries Oceanography 13: 310-323.

Field J. C. and Balz K. A. 2007. The jumbo squid, *Dosidicus gigas*, a new groundfish predator n the Californian Current? In: Robert J. Olson and Jock W. Young (Eds.) 2007. The role of squid in open ocean ecosystems. Report of a GLOBEC-CLIOTOP/PFRP workshop, 16-17 November 2006, Honolulu, Hawaii, USA. GLOBEC Report 24: vi, 94 pp.

References

Herzfeld M. and Tomczak M. 1997. Numerical modelling of sea-surface temperature and circulation in the Great Australian Bight. Progress in Oceanography 39: 29-78.

Hobday A.J. 2001. The influence of topography and environment on presence of juvenile southern bluefin tuna, *Thunnus maccoyii,* in the Great Australian Bight, Southern Bluefin Tuna Recruitment Monitoring Workshop Report. CSIRO Marine Research, Hobart, Australia.

Hobday A.J., Hartmann K., Bestley S., Tsuji S. and Takahashi N. 2004. Integrated analysis project - environmental influences on the observed decline of southern bluefin tuna in the acoustic survey area. Southern Bluefin Tuna Recruitment Monitoring Workshop Report, Yokohama, Japan, CSIRO Marine Research, Hobart, Australia.

Hobday, A. J. and K. Hartmann (2006). Near real-time spatial management based on habitat predictions for a longline bycatch species. Fisheries Management & Ecology 13: 365-380.

Hunt G.L. and McKinnell S. 2006. Interplay between top-down, bottom-up, and wasp-waist control in marine ecosystems. Progress in Oceanography 68: 115-124.

Jackson G.D. and Domeier M.L. 2003. The effects of an extraordinary El Niño/La Niña event on the size and growth of the squid *Loligo opalescens* off Southern California. Marine Biology 142: 925-935.

Jackson G.D., McGrath Steer B., Wotherspoon S. and Hobday A.J. 2003. Variation in age, growth and maturity in the Australian arrow squid *Nototodarus gouldi* over time and space—what is the pattern? Marine Ecology Progress Series 264: 57-71.

Jacobson L.D., De Oliveira J.A.A., Barange M., Cisneros-Mata M.A., Félix-Uraga R., Hunter J.R., Kim J.Y., Matsuura Y., Ñiquen M., Porteiro C., Rothschild B., Sanchez R.P., Serra R., Uriarte A. and Wada T. 2001. Surplus production, variability, and climate change in the great sardine and anchovy fisheries. Canadian Journal of Fisheries and Aquatic Sciences 58: 1891-1903.

Kitagawa T., Sartimbul A., Nakata H., Kimura S., Yamada H. and Nitta A. 2006. The effect of water temperature on habitat use of young Pacific bluefin tuna *Thunnus orientalis* in the East China Sea. Fisheries Science 72: 1166-1176.

Larcombe J. and McLoughlin K. Eds. 2007. Fishery Status Reports 2006: Status of Fish Stocks Managed by the Australian Government. Bureau of Rural Sciences, Canberra.

Laurs R.M., Fiedler P.C. and Montgomery D.R. 1984. Albacore tuna catch distributions relative to environmental features observed from satellites. Deep-Sea Research 31: 1085-1099.

Lehodey P., Bertignac M., Hampton J. Lewis A. and Picaut J. 1997. El Niño Southern Oscillation and tuna in the western Pacific. Nature 389: 715-718.

Lyle J., Krusic-Golub K. and Morison A. 2000. Age and growth of jack mackerel and the age structure of the jack mackerel purse seine catch. FRDC Final Report 1995/034. University of Tasmania.

Majkowski J., Williams K. and Murphy G.I. 1981. Research identifies changing patterns in Australian tuna fishery. Australian Fisheries 40: 5-10.

Olson R.J. and Young J.W. Eds. 2007. The role of squid in open ocean ecosystems. Report of a GLOBEC-CLIOTOP/PFRP workshop, 16-17 November 2006, Honolulu, Hawaii, USA. GLOBEC Report 24: vi, 94pp.

Pecl G.T. and Jackson G.D. 2005. The potential effects of climate change on southern calamary in Tasmanian waters: biology, ecology and fisheries (presentation to WWF). Marine Research Laboratory, University of Tasmania.

Reddy R., Lyne V., Gray R., Easton A. and Clarke S. 1995. An application of satellite-derived sea surface temperatures to southern bluefin tuna and albacore off Tasmania, Australia. Scientia Marina 59: 445-454.

Rose G.A. 2005. On distributional responses of North Atlantic fish to climate change. ICES Journal of Marine Science 62: 1360-1374.

Sarmiento J.L., Gruber N., Brzezinski M.A. and Dunne J.P. 2004. High-latitude controls of thermocline nutrients and low latitude biological productivity. Nature 427: 56-60.

Schick R.S., Goldstein J. and Lutcavage M.E. 2004. Bluefin tuna (*Thunnus thynnus*) distribution in relation to sea surface temperature fronts in the Gulf of Maine (1994-96). Fisheries Oceanography 13: 225-238.

White W.B., Gloersen K.A., Marsac F. and. Tourre Y.M 2004. Influence of Coupled Rossby Waves on Primary Productivity and Tuna Abundance in the Indian Ocean. Journal of Oceanography 60: 531-541.

Young, J. W., R. W. Bradford, T. D. Lamb, L. A. Clementson, R. Kloser and H. Galea (2001). Yellowfin tuna (Thunnus albacares) aggregations along the shelf break off south-eastern Australia: links between inshore and offshore processes. Marine and Freshwater Research 52: 463-474.

Young J.W., Jordan A.R., Bobbi C., Johannes R.E., Haskard K. and Pullen G. 1993. Seasonal and interannual variations in krill (*Nyctiphanes australis*) stocks and their relationship to the fishery for jack mackerel (*Trachurus declivis*) off eastern Tasmania, Australia. Marine Biology 116: 9-18

Young J.W., Bradford R.W., Lamb T.D. and Lyne V.D. 1996. Biomass of zooplankton and micronekton in the southern bluefin tuna fishing grounds off eastern Tasmania, Australia. Marine Ecology Progress Series 138: 1-14.

Young J.W. and Hobday A.J. 2004. Determining ecological effects of longline fishing in the Eastern Tuna and Billfish fishery. Progress report. FRDC Project 2004/063. CSIRO Marine Research.

Young J.W., Lamb T.D., Bradford R., Clementson L., Kloser R. and Galea H. 2001. Yellowfin tuna (*Thunnus albacares*) aggregations along the shelf break of southeastern Australia: links between inshore and offshore processes. Marine and Freshwater Research 52: 463–474.

Zagarese H.E. and Williamson C.E. 2001. The implications of solar UV radiation exposure for fish and fisheries. Fish and Fisheries 2: 250-260.

Sub-Antarctic Fisheries

Agnew D.J. and Nicol S. 1996. Marine disturbances: Commercial fishing. Foundation for Ecological Research West of the Antarctic Peninsula, Antarctic Research Series 70: 417-435.

Arrigo K.R. and Thomas D.N. 2004. Large-scale importance of sea ice biology in the Southern Ocean. Antarctic Science 16: 471-486.

Arrigo K.R., Worthen D., Schnell A. and Lizotte M.P. 1998. Primary production in Southern Ocean waters. Journal of Geophysical Research 103(C8): 15,587-15,600.

Atkinson A., Siegel V., Pakhomov E. and Rothery P. 2004. Long-term decline in krill stock and increase in salps within the Southern Ocean. Nature 432: 103.

Caldeira K. & Wickett M.E. 2005. Ocean model predictions of chemistry changes from carbon dioxide emissions to the atmosphere and ocean. Journal of Geophysical Research – Oceans 110, C09S04.

Croxall J.P. and Nicol S. 2004. Management of Southern Ocean fisheries: global forces and future sustainability. Antarctic Science 16: 569-584.

Duhamel G. and Hureau J.C. 1985. The role of zooplankton in the diets of certain sub-Antarctic marine fish. In: Siegfrid W.R., Condy P.R. & Laws R.M. (eds) *Antarctic nutrient cycles and food webs*. Springer: Berlin, pp 430-436.

Engel A., Zondervan I., Aerts K., Beaufort L., Benthien A., Chou L., Delille B., Gattuso J.P., Harlay J., Heemann C., Hoffmann L., Jacquet S., Nejstgaard J., Pizay M.D., Rochelle-Newall E., Schneider U., Terbrueggen A. & Riebesell U. 2005. Testing the direct effect of CO_2 concentration on a bloom of the coccolithophorid *Emiliania huxleyi* in mesocosm experiments. Limnology and Oceanography 50: 493-507.

Everett J.T and Fitzharris B.B. 1998. The Arctic and the Antarctic. In: *The Regional Impacts of Climate Change. An Assessment of Vulnerability. A Special Report of IPCC Working Group II for the Intergovernmental Panel of Climate Change* [Watson, R.T, M.C. Zinyowera, R.H. Moss and D.J. Dokken (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 85-103.

Fitch D.T. and Moore J.K. 2007. Wind speed influence on phytoplankton bloom dynamics in the Southern Ocean Marginal Ice Zone. Journal of Geophysical Research 112, Art C08006.

Goldsworthy S.D., Lewis M., Williams R., He X., Young J.W. and van den Hoff J. 2002. Diet of Patagonian toothfish (*Dissostichus eleginoides*) around Macquarie Island, South Pacific Ocean. Marine and Freshwater Research 53: 49-57.

Hender J. and Larcombe J. 2007a. Heard Island and McDonald Islands Fishery, pp195-203. In Larcombe, J. and McLoughlin, K. (eds) (2007) *Fishery Status Reports 2006: Status of Fish Stocks Managed by the Australian Government.* Bureau of Rural Sciences, Canberra.

Hender J. and Larcombe J. 2007b. Macquarie Island Toothfish Fishery, pp230-232. In Larcombe, J. and McLoughlin, K. (eds) (2007) *Fishery Status Reports 2006: Status of Fish Stocks Managed by the Australian Government.* Bureau of Rural Sciences, Canberra.

Hender J. and Larcombe J. (2007c) Antarctic waters, pp256-257. In Larcombe, J. and McLoughlin, K. (eds) (2007) *Fishery Status Reports 2006: Status of Fish Stocks Managed by the Australian Government.* Bureau of Rural Sciences, Canberra.

Hill S.L., Reid K. and North A.W. 2005. Recruitment of mackerel icefish (*Champsocephalus gunnari*) at South Georgia as indicated by predator diets and its relationship with sea surface temperature. Canadian Journal of Fisheries and Aquatic Sciences 62: 2530-2537.

References

Hennessy K.B., Fitzharris B., Bates B., Harvey N., Howden S.M., Hughes L., Salinger J. and Warrick R. 2007. Australia and New Zealand. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* M.L. Parry, O.F. Canziani, J.P. van der Linden and C.E. Hanson eds. Cambridge University Press, Cambridge, UK, 507-540.

IPCC 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor M and H.L. Miller (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996pp.

Kikkawa T., Ishimatsu A. and Kita J. 2003. Acute CO_2 tolerance during the early developmental stages of four marine teleosts. Environmental Toxicology 18: 375-382.

Kock K-H. 2005. Antarctic icefishes (Channichthyidae): a unique family of fishes. A review, Part I. Polar Biology 28: 862-895.

Kock K-H. and Everson I. 2003. Shedding new light on the life cycle of mackerel icefish in the Southern Ocean. Journal of Fish Biology 63: 1-21.

Loeb V.V.S., Holm Hansen O., Hewitt R., Fraser W., Trivelpiece W. and Trivelpiece S. 1997. Effects of sea ice extent and krill or salp dominance on the Antarctic food web. Nature 387: 897-900.

McKenna J.E. 1991. Trophic relationships within the Antarctic demersal fish community of South Georgia Island. Fishery Bulletin 89: 643-654.

Moline M.A., Claustre H., Frazer. T.K., Schofield O. and Vernet M. 2004. Alteration of the food web along the Antarctic Peninsula in response to a regional warming trend. Global Change Biology 10: 1973-1980.

Moore J.K. and Abbott M.R. 2000. Phytoplankton chlorophyll distributions and primary production in the Southern Ocean. Journal of Geophysical Research 105(C12): 28,709-28,722.

Nicol S. 2006. Krill, currents and sea ice; the life cycle of *Euphausia superba* in relation to its changing environment. Bioscience 56: 111-120.

Nicol S., Worby A. and Leaper R. 2007. Changes in the Antarctic sea ice ecosystem: potential effects on krill and baleen whales. (under review)

Nicol S, Kitchener J, King R, Hosie GW and de la Mare WK 2000. Population structure and condition of Antarctic krill (*Euphausia superba*) off East Antarctica (80-150°E) during the Austral summer of 1995/6. Deep-Sea Research II 47: 2489-2517.

North A.W. 2005 Mackerel icefish size and age differences and long-term change at South Georgia and Shag Rocks. Journal of Fish Biology 67: 1666-1685.

Orr J.C., Fabry V.J., Aumont O., Bopp L., Doney S.C., Feely R.A., Gnanadesikan A., Gruber N., Ishida A., Joos F., Key R.M., Lindsay K., Maier-Reimer E., Matear R., Monfray P., Mouchet A., Najja, R.G., Plattner G.K., Rodgers K.B., Sabine C.L., Sarmiento J.L., Schlitzer R., Slater R.D., Totterdell I.J., Weirig M.F., Yamanaka Y. & Yool A. 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature 437: 681-686.

Pedersen M.F. & Hansen P.J. 2003. Effects of high pH on a natural marine planktonic community. Marine Ecology Progress Series 260: 19-31.

Pörtner H.O., Langenbuch M. & Reipschläger A. 2004. Biological impact of elevated ocean CO_2 concentrations: Lessons from animal physiology and earth history. Journal of Oceanography 60: 705-718.

Riebesell U., Zondervan I., Rost B., Tortell P.D., Zeebe R.E. & Morel F.M.M. 2000. Reduced calcification of marine plankton in response to increased atmospheric CO_2. Nature 407: 364-367.

Roessig J.M., Woodle C.M., Cech J.J. & Hansen L.J. 2004. Effects of global climate change on marine and estuarine fish and fisheries. Reviews in Fish Biology and Fisheries 14: 251-275.

Sloyan B.M. and Rintoul S.R. 2001. The Southern Ocean Limb of the Global Deep Overturning Circulation. Journal of Physical Oceanography 31: 143-173.

Walton D.W. 1987. Antarctic Science. Cambridge University Press, Cambridge.