National Marine Science Plan, White paper submissions for Biodiversity Conservation and Ecosystem Health

Climate Change Impacts

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Background

Anthropogenic greenhouse gas emissions are interfering with the climate system, and altering ocean physics and chemistry. Warming of the climate system is unequivocal and many of the changes observed in recent decades are unprecedented over decades to millennia (IPCC, 2013). Climate change impacts have been detected in natural and human systems on all continents and in all oceans (IPCC, 2014). Both globally and in Australian waters, marine species have shifted their geographic ranges, seasonal activities, migration patterns, abundance and species interactions in response to ongoing climate change (Poloczanska *et al.*, 2007; Poloczanska *et al.*, 2013; Hoegh-Guldberg *et al.*, 2014; Poloczanska *et al.*, 2014). Observations are however severely limited by available data, especially historical data, and so impacts are very likely severely under-reported.

Climate change impacts on marine ecosystems represent risks for marine industries such as fishing and the persistence of marine ecosystems, and threaten coastal population centres and infrastructure (Bell *et al.*, 2011b; Hoegh-Guldberg *et al.*, 2014; Steffen *et al.*, 2014). Some species and marine industries may benefit from climate change, without further human intervention, but the evidence suggests these will be rare (IPCC, 2014). Climate change is projected to amplify existing climate-related risks, exacerbate the impacts on non climate-related stressors and create new risks for natural ecosystems and the services they provide, thus complicating marine management regimes (IPCC, 2014). Ensuring flexible adaptation strategies in policies and planning is essential for the continuing sustainability of marine resources and services and, in some cases, to benefit from ongoing changes (Poloczanska *et al.*, 2012; FRDC, 2014; GBRMPA, 2014). Adaptation needs to be embedded in decision-making as part of a broader management process (Pecl *et al.*, 2014). For many ecosystems and industries, key research gaps exist around vulnerability and risks, barriers to adaptation and potential for risk-reduction through implementation of adaptation strategies (Hodgkinson *et al*. 2014).

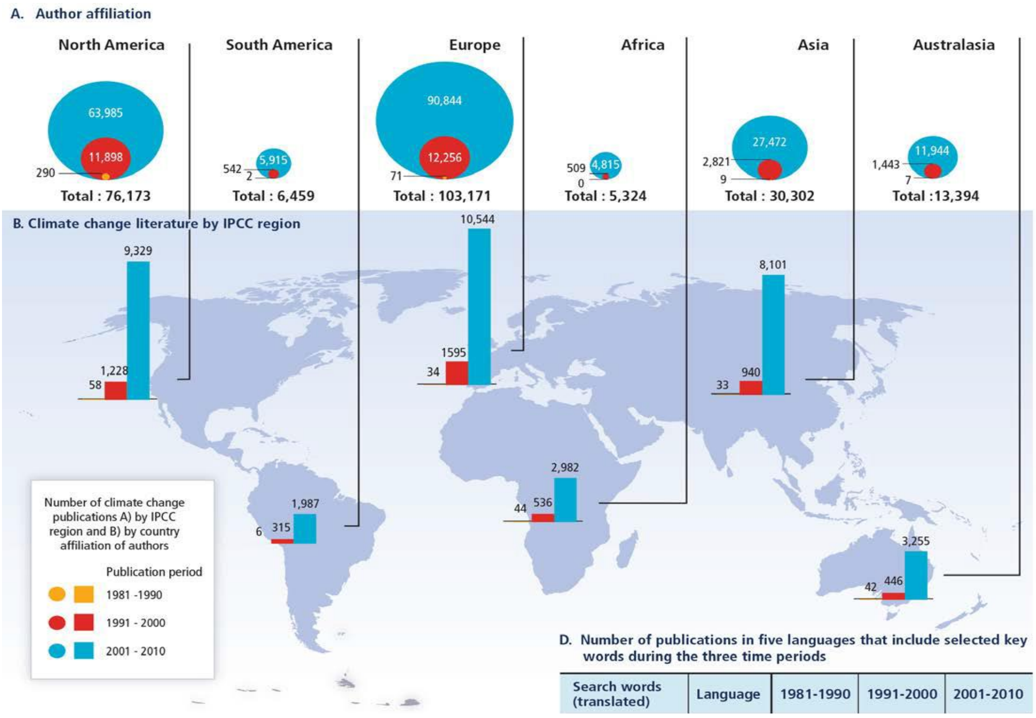

Figure 1: A. Author country affiliations in climate change literature (1991-2010) cited in IPCC AR5 Working Group II: Impacts, Vulnerability and Adaptation, including marine-focused literature. For perspective, Australasia (Australia and New Zealand) has ~3% of the population of both Europe and North America (includes Mexico) and produced a climate change literature equivalent to 13% of European and 18% of North American outputs. B. Number of climate change publications in English with individual countries mentioned in title, abstract or keywords binned into IPCC regions. From (Burkett *et al.*, 2014).

Australia makes a significant international contribution to the understanding of physical and chemical changes in the ocean (e.g. CSIRO & Australian Bureau of Meterology, in press; also see Dealing with Climate Change white paper) as well as understanding of biological changes and research of impacts, vulnerability and adaptation for ecosystems and marine industries (Fig. 1). Approximately 12% of 8292 ‘marine climate change’ papers published since 2004 include Australian researchers among author teams. Australia’s scientists contribute to high-profile international documents including the Assessment Reports and Special Reports of the Intergovernmental Panel on Climate Change (www.IPCC.ch) and syntheses assimilated by the Convention on Biological Diversity (CBD), the United Nations body committed to the conservation and sustainable use of all forms of life on Earth (www.cbd.int).

Most research institutions in Australia have researchers and/or programs that address the impacts of climate change, with major groups of researchers from CSIRO, Australian Institute of Marine Sciences, Australian Antarctic Division, Geosciences Australia, State governments and across the universities including (but not restricted to) Australian National University, Curtin University, Flinders University, James Cook University, Southern Cross University, Sydney University, University of Adelaide, University of New South Wales, University of Queensland, University of Tasmania, Wollongong University and University of Western Australia. Australia has the potential to be a world-leader in most aspects of climate change research, given the strength and quality across diverse research areas. Australian scientists cover a broad range of latitudes, taxonomic groups and habitats from tropical coral reefs to Antarctica, in their research.

Australian universities and research organisations have world-class expertise in climate and ocean observations and modelling, regional oceanography and ecology, ecosystem modelling, ocean acidification research, coral reef ecology, climate adaptation research, conservation science, fisheries research, marine economics and social science. Research facilities and partnerships such as the National Climate Change Adaptation Research Facility (NCCARF), Fisheries Research and Development Corporation (FRDC) and the (now defunct) CSIRO Climate Adaptation Flagship (CAF), have not only extended interdisciplinary research but have also facilitated integration of research into adaptation planning and policymaking. Initiatives such as the Pacific-Australian Climate Change Science and Adaptation Planning Program (PACCSAPP http://www.pacificclimatechangescience.org/) have enhanced the capacity in the wider SW Pacific region to understand and build resilience to climate change impacts (Australian Bureau of Meterology & CSIRO, 2014). The fully-integrated array of observing equipment administered by the Integrated Marine Observing System (IMOS http://imos.org.au/) is monitoring open and coastal oceans. The Australian plan for Earth Systems Science, bringing together Australian and international expertise across diverse research disciplines, will enable research to understand and inform adaptation and mitigation of current and future global changes (Gifford *et al.*, 2010).

Research is funded by the Australian Government (e.g. DoE, DAFF, FRDC), through funding to research providers such as ARC and National Environmental Research Program (and subsequent National Environmental Science Program), through State Governments and Agencies, and through federal funding to CSIRO Research Flagships, National Facilities and AIMS. NGOs (e.g. Great Barrier Reef Foundation, Moore Foundation) also play a role.

Relevance

Australian researchers directly contribute to planning and policy decisions regarding climate change, e.g. the Australian Government's vulnerability assessment for the Great Barrier Reef (Johnson & Marshall, 2007) which continues to inform current management approaches; vulnerability of Pacific fisheries which set a benchmark assessment for Pacific fisheries and future food security (Bell *et al.*, 2011a); and through activities supported by research and development partnerships (e.g. Climate change adaptation – marine biodiversity and fisheries R&D initiative (FRDC, 2014)).

- **Government and community:** The federal government uses climate change science to inform mitigation and adaptation policies. The science provides a guide for the community to align activities that deliver national benefit (DCCEE, 2012).

- **Fishing industry:** The effects of climate change on many fish stocks are uncertain given the current state of knowledge, but a growing body of work is informing robust fisheries management. One of the industry concerns relates to the uncertainty in the extent of ecosystem effects and the timeframes in which such effects might be problematic (Hobday & Evans, 2013). An action plan for Australian fisheries was released in 2011 (http://www.agriculture.gov.au/fisheries/environment/climate_change_and_fisheries/cc-action-plan-fish-aquaculture) but was not associated with any funding, however, the recently completed NCCARF-DCCEE-FRDC research portfolio consisted of some 25 research projects addressing climate, fishing, and marine biodiversity. Increasing understanding of the effect of climate change on the marine environment and fish populations and developing responsive and flexible approaches will improve regulations and actions, diminish the risk of economic loss, and improve adequate management of resources for the future (Hobday & Salinger, 2013; Holbrook & Johnson, 2014). Impacts further up the supply chain also impact on fisheries (Lim-Camacho *et al*., 2014), and approaches to identify and minimize these effects have been developed (Plaganyi *et al*., 2014).

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- **Tourism industry:** Tourism is a growing industry in Australia that generates millions of dollars including that linked to ecotourism activities (Tourism Research, 2014). The marine industry is a major contributor to local and national economies. For example, there were almost 1.9 million visitor days to the Great Barrier Reef region in 2013 – 64% with independently managed eco-certified operators (GBRMPA, 2014). Tourism associated with the ocean is heavily influenced by climate change, global economic and socio-political conditions, and the interactions among these. Climate change, through impacts on ecosystems, can reduce the appeal of destinations, increase operating costs, and/or increase uncertainty in a highly sensitive business environment. Investigation of the vulnerabilities and risks from climate change will assist adaptation of the tourism industry (Marshall *et al*., 2013).

- **Marine conservation:** Climate change is changing the perspective of many conservation managers. A preserve and protect approach may no longer be appropriate under climate change. Autonomous movements of species and habitats into new regions will affect a range of conservation efforts (Burrows *et al.* 2014). Translocation is being actively considered for some species, and a range of direct interventions may be needed for others (Hobday *et al.*, 2014).

- **Maritime operations including recreational, navy, oil and gas and shipping:** Many maritime operations and industries, such as oil and gas, carry risks to marine species that must be managed with a foresight of predicted changes, and approved through the government. Predicting changes in species distribution and migration due to climate change will inform and improve management of industry and maritime operations (Redfern *et al*., 2012).

Science Needs

Science needs were identified in Chapter 30 The Ocean in Working Group II (WGII) of the Intergovernmental Panel on Climate Change Fifth Assessment Report (AR5) (Hoegh-Guldberg *et al.*, 2014) and the Australian Marine Climate Change Report Cards (Poloczanska *et al.*, 2009, 2012). Chapter 25 Australasia of AR5 WGII also presents marine issues arising from climate change (Reisinger *et al.*, 2014). A summary is given below, which includes ocean acidification, also a result of increasing anthropogenic CO_2 in the atmosphere:

1. Long-term climate variability and extreme climatic events.
Natural climatic variability in the Australian region manifests as a result of climate phenomena, including the El Niño-Southern Oscillation, the Indian Ocean Dipole, the Interdecadal Pacific Oscillation and the Southern Annular Mode (Risbey *et al.*, 2009). The interplay among these climate

phenomena influences regional climates including ocean temperature and ocean current strength and the occurrence of climatic extreme events such as heatwaves, floods and tropical cyclones (CSIRO & Australian Bureau of Meterology, 2014; in press). Understanding the behaviour of climate phenomena under changes in atmospheric concentration of greenhouse gases, including CO_2, and the short- and long-term consequences for marine ecosystems and industries is a key science gap. However, the recently completed projections for Australia (CSIRO & Australian Bureau of Meterology, in press) provide a robust basis for further work. Observed responses to climatic extremes demonstrate the vulnerability and exposure of some marine systems to current climate variability. There is clear evidence that impacts of climatic extremes can be severe, with consequences for marine industries (Wernberg *et al.*, 2013). For example, the 2010/2011 'marine heatwave' off Western Australia had measurable impacts on marine community structure (Wernberg *et al.*, 2013). Similarly, recent severe weather events (floods associated with La Niña events and tropical cyclones) have had observable impacts on the Great Barrier Reef World Heritage Area (GBRMPA, 2014). Heat stress events are known to be devastating for coral reefs, leading to bleaching and mortality by the reef building corals. Extreme events, such as thermal stress events, are increasing in frequency (Zinke *et al.*, 2014). While it is clear that climate change will impact the structure and function of marine ecosystems, the exact nature of such responses, including the particular system-specific ramifications, timing and magnitude of responses, and capacity for acclimatization and biological adaptation, are still largely unknown. Management and planning processes are starting to incorporate forecasts of climate and ocean variability (e.g., Spillman & Hobday, 2014; Hobday *et al.*, 2011, http://poama.bom.gov.au/marine_mw/prawn_project.shtml). A significant knowledge gap exists around the adaptation strategies required to minimize the impact of extreme climatic events on ecosystem goods and services and foster ecosystem resilience.

2. Responses of coastal ecosystems and climate change mitigation.

Rising sea levels will result in inundation of low-lying regions and erosion of coastal soft sediments, exacerbated where wave height increases. Rapid sea-level rise poses a serious threat to coastal ecosystems, communities and infrastructure. Understanding of regional risks and vulnerabilities and the effectiveness of adaptation strategies, such as warning systems developed through the operational application of storm-surge modeling, is a near-term research priority that requires major investment for the production of outputs at spatial and temporal resolutions for effective decision-making. Tidal wetlands (seagrass, mangroves, saltmarsh), beaches and low-lying coral atolls and islands are extremely sensitive to sea-level rise, and research priorities exist around regional vulnerabilities to sea-level rise and other stressors (Schlacher *et al.*, 2007; Schoeman *et al.*, 2014). Investigation of the interdependencies between coastal ecosystems will improve understanding of risks to coastal systems and communities (Saunders *et al.*, 2014). Understanding the impacts of the continual degradation and loss of coastal habitats under a changing climate, including consideration of the loss of productivity and ecosystem services, is required. There is also potential for marine ecosystems to play a role in climate change mitigation though carbon sequestration and storage by marine plants, known as "Blue carbon" (http://thebluecarboninitiative.org/). International efforts to develop policy options around incentives based on Blue Carbon are accelerating, but are hampered by major research gaps around carbon storage rates and sink capacity (McLeod *et al.*, 2011; Ullman *et al.*, 2013).

3. How will regional primary production change

How regional primary production is likely to change in a warmer and more acidified ocean has implications for ecosystem functioning. Research gaps exist around the spatial and temporal variability of phytoplankton community structures and how these are likely to change under climate change scenarios. Only 13% of experimental studies to establish understanding of climate change effects have tested plankton (Wernberg *et al.*, 2012). Understanding changes at the ocean–atmosphere interface and climate change effects on biogeochemical processes will provide important insights on changes in primary productivity. Terrestrial processes, such as flood events and land-use change, can have large impacts on nutrient availability and thus primary production in coastal waters. Changes in regional productivity will resonate through food webs and ultimately affect fish and shellfish production (Brown *et al.,* 2009). Research efforts are required to provide understanding of the role of primary production in supporting Australian fisheries production under climate change scenarios (Fulton, 2011). Another important consideration is the footprint of upstream activities. Global change (including human population changes and increased pressure for industrial development, energy and food security) will see further modification and intensification in use of catchments. The outflow of these areas, in combination with estuarine and marine releases from industries could also significantly modify nearshore productivity. Intensifying drought-flood cycles could also increase the loss of nutrients, fertilisers and soils into the coastal marine environment. Expanding research efforts to understand catchment to coast linkages under scenarios of land-use and climate change will inform adaptation planning and management decisions (e.g., see Estuaries white paper).

4. Microbes and oxygen

Microbes are central to the global biogeochemical cycles and therefore play a critical role in either mitigating or exacerbating the effects of climate change. Oxygen concentrations have decreased in the upper layers of the ocean since the 1960s, particularly in the equatorial Pacific (Hoegh-Guldberg *et al.*, 2014). Analyses of oxygen trends in the upper ocean reveal around 15% of the global oxygen decrease can be explained as a warmer surface layer reducing the capacity of water to store oxygen, and the remaining 85% of the decline is associated with increased deep-sea microbial respiration and reduced exchange between surface waters and the ocean interior through increased stratification caused by warmer surface waters (Helm *et al.*, 2011). Modelling studies suggest continuing declines in oxygen levels have reduced the available habitat for exploited fish such as tuna in the equatorial Pacific (Stramma *et al.*, 2012) and globally reduced fisheries catch potential (Cheung *et al.*, 2011). Australia has no long-term records documenting the community dynamics of bacteria, viruses and other microorganisms and, in fact, very few such datasets exist globally. Marine microorganisms are able to respond very rapidly to changing environmental conditions, and they have the ability to rapidly evolve making them potential bio-indicator organisms. Developing a better understanding of the role and temperature sensitivity of microbial systems in determining oxygen concentrations (as well as nitrogen fixation, which will become increasingly important in a warmer, more stratified ocean) will enable a more coherent understanding of the changes and potential risks to marine ecosystems, including commercial fisheries and deep-sea ecosystems.

5. Species responses to climate change

Temperature has a fundamental influence on all chemical and biological processes and for many marine organisms. There is very high confidence that Australia's oceans will continue to warm (CSIRO & Australian Bureau of Meterology, in press). A major goal for marine climate change research is to determine if individual populations and communities can persist at present day levels when they are exposed to future climates. Climate change stressors include warming temperatures, and increasing frequency and intensity of temperature extremes. Species can respond to warming and other changes in the ocean environment in a number of ways, e.g. shifting phenology, changes in abundance and distribution, alteration of reproductive or growth rates, physiological or genetic adaptations (Parmesan, 2006; Poloczanska *et al.*, 2013). Our understanding of species' vulnerability to climate change, such as physiological/behavioural responses and thresholds, is lacking. Which species and ecosystems are responding, how they are responding and the potential for social and economic ramifications (e.g. (Madin *et al.*, 2012), including implications for fisheries catch, jurisdictional management, biosecurity as well as conservation planning, is a key research gap. Climate change effects on movements and migration patterns, population size and health of large marine fauna such as whales, dolphins, pinnipeds, turtles, sharks, and rays has implications for threatened species recovery and reliant ecotourism industries (DEWHA, 2010). One of the most widely documented impacts of climate change is a shift in species distributions (Poloczanska *et al.*, 2014). Modelling studies project that global warming will affect the distribution of biodiversity (Cheung *et al.*, 2010; Burrows *et al.*, 2014) with regional net gains or losses of species richness depending on the climate change scenario followed (Fig. 2). Understanding how predicted climate change will affect the distribution of biodiversity is critical to anticipate changes to ecosystem structure and function in particular areas and the goods and services provided to human populations (Bates *et al*., 2014). The potential for climate change to drive shifts in phenology (timing of life cycle events) are less understood for most marine species (O'Connor *et al.*, 2014), but will have implications for food webs (e.g., through abundance of predators or prey) and marine conservation and management (e.g. temporal closures of spawning grounds, fishery seasons). A developing research area, yet one that is important to understanding climate impacts on marine biodiversity, is whether genetic adaptations and non-genetic transgenerational changes are occurring, and whether they are capable of keeping pace with the rates of change in the climate system. Developing a better understanding of how biological and ecological properties change in relation to key environmental variables should be a goal of future research.

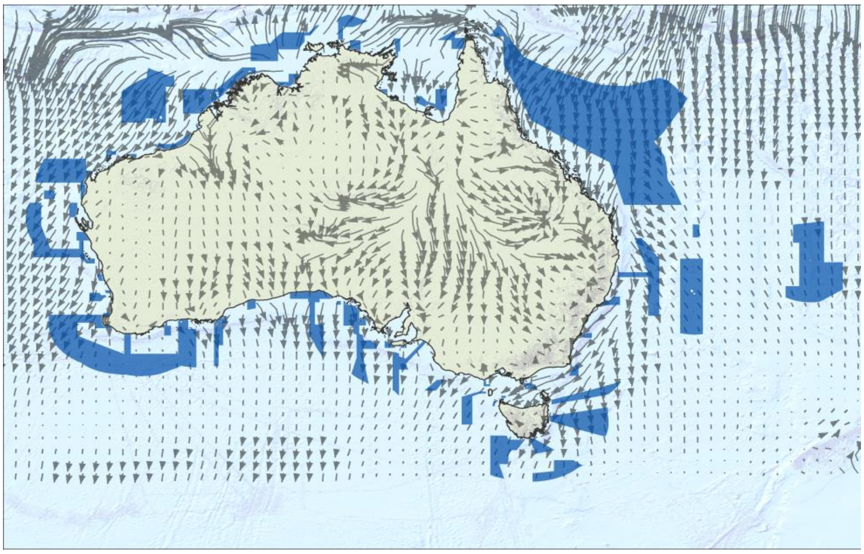

Figure 2. Observed shift in isotherms (1960-2009) over Australia's land and sea surface (adapted from (Burrows *et al*., 2014) showing the trajectories followed (grey arrows) as a proxy for the expected rate and direction of shifts in marine species distributions. The network of Commonwealth marine reserves is displayed (dark blue).

6. Ocean acidification

Ocean acidification, alone and in combination with other drivers, influences the behaviour, growth, development and/or survival of marine species. Marine carbonate chemistry and pH are known to play important roles in key physiological processes (e.g. calcification in corals and shellfish, acid/base balance, external fertilisation, etc.). There are a growing numbers of laboratory and some field studies that demonstrate a broad range of negative effects of ocean acidification on organisms and ecological processes but the long-term consequences on organisms and on ecosystems, and the interactive effects with other drivers of change are key research gaps (CBD, 2014). Most conclusions about biological responses to ocean acidification come from laboratory manipulations rather than observations. They show that responses on growth, development, survival, and neurological performance can vary widely within and between species (Byrne, 2011; Byrne & Przeslawski, 2013). Understanding of how carbonate structures (eg coral reefs, deep water corals on sea mounds, mussle beds, Halimeda meadows) will respond to a rapidly acidifying ocean, especially in terms of understanding the rate at which consolidated carbonate structures and related habitats are likely to erode and dissolve and when, are big research gaps. There is also a need to understand the effects of increased carbon availability to carbon-limited primary producers (Connell *et al.*, 2013). Changing pH also influences other important aspects of seawater chemistry, such as the availability of carbon, nitrogen and iron (both necessary for primary production). Although seagrasses and marine macroalgae (macro-autotrophs) play critical ecological roles in reef, lagoon, coastal and open-water ecosystems, their response to ocean acidification (and climate change) is not well understood. A natural laboratory with CO_2 seeps in Papua New Guinea has, however, provided key insights into how coral reef communities may respond to future levels of ocean acidification (e.g. Fabricius *et al.*, 2011; Munday *et al.*, 2014) with insights into temperate systems from the vents at Ischia, Italy (Kroeker *et al*., 2011). Similar knowledge is sparse for Australia's many temperate marine ecosystems. Key questions also remain around the capacity for key species to genetically adapt to ocean acidification, including which organisms and ecosystems have or will be impacted and how will these impacts on species upscale to ecosystem effects? To answer these questions, models of community dynamics must be developed from observational data on the performance of key species over historical timescales and their ecological interactions under future conditions (Munday *et al.*, 2013). Overall responses of taxa to ocean acidification and warming can be highly variable (Kroeker *et al.*, 2013) and thus difficult to predict, but responses may have significant implications for economically-important ecosystems and fisheries. There is also a need to understand whole-of system responses. For example, to identify taxa that are more robust, or to determine the capacity of natural ecosystem to offset or buffer impacts through metabolic processes (e.g., respiration within seagrass beds) and the ecosystem consequences of ocean acidification impacts.

7. Cumulative and synergistic interactions.

Human impacts in the ocean, such as anthropogenic climate change, fishing and pollution, are pervasive (Halpern *et al.*, 2008) and lead to concurrent changes in a range of environmental variables. Much of our understanding of species responses to climate change has been built on experimental approaches that are focused on single stressors that respond gradually without interactions or impacts that accumulate over time (Wernberg *et al.*, 2012). Multifactorial experiments and models exploring the impact of combined variables (e.g., warming and acidification, warming and exploitation, at the same time) have their problems (Parmesan *et al.*, 2013), but will enable more realistic projections of the future to be established (Boyd, 2013; Byrne & Prezlawski, 2013). Understanding of ecological thresholds, where rapid and transformational changes can occur, and the cumulative and synergistic interactions of climate change and other stressors in driving ecosystem change is an urgent research goal.

8. The potential reorganisation of foodwebs and implications for management.

Climate change will reorganize marine food webs and alter ecosystem function, with attendant impacts on marine industries and activities. Differing tolerances and responses among species to climate change and ocean acidification will exacerbate the global trend to the emergence of novel assemblages of species due to anthopogenic pressures in the near future. Along with changing human use of catchments and oceans this will necessitate new strategies for managing coastal areas and fisheries. Regional ecosystem models provide scope to forecast changes in biological systems and their socio-economic consequences, thereby informing management and policy (Plaganyi *et al.*, 2013). To prepare for such changes, approaches such as reviews of fisheries management to examine robustness to climate change and identify potential adaptation pathways, and the development of smart and real-time stock assessment and population predictions (FRDC, 2014).

9. Economic, social and legal consequences

The vulnerability of fisheries and other marine activities to climate change remains a crucial issue, with a need for research to understand and develop strategies for industries to minimize the impacts and profit where opportunities arise (FRDC, 2014). Enhancing national capacity for seasonal, multi-year and decadal marine forecasting and ocean current/eddy forecasting will enhance marine user decisions. Improvements to our understanding and the communication of trajectories of change in marine environments and industries are needed to underpin management and policy decisions. Research to develop adaptive and flexible management systems, and enhance market (economic) and industry development under climate change. Within the wider region, the Indonesian Through Flow (ITF) is a major driver of ocean productivity and fisheries production. However, while the region is characterized by high levels of food insecurity, the impacts of climate change on the ITF, and particularly fisheries production, is unclear. In northern Australia, there is also strong customary and cultural dependence on coastal and marine resources by Indigenous communities. There is a need to investigate the trans-boundary biophysical and socio-economic impacts of climate change in the Arafura-Timor Seas region with its 'shared' fish stocks, seascapes and "threatened, endangered and protected" (TEP) species. For the millions of people in the wider SE Asia and Pacific region who depend on coastal ecosystems for food and livelihoods, there is relatively poor understanding of the socio-economic and cultural implications of climate change on these ecosystems, and onflow of economic and social implications for Australia. Major advances in scientific understanding of past and future climate change in the region have been made in recent years (Australian Bureau of Meterology & CSIRO 2011, 2014). The Australian government has also supported significant capacity building efforts in Pacific island and Asian Least Developed Countries since 2009 (http://www.pacificclimatechangescience.org/; http://www.bom.gov.au/cosppac/). Enhancing resilience in these communities, in terms of food security and economic security, is vital for the security of the whole region. Accordingly, it is important to build on the momentum created by previous programmes. We also need to understand legal implications that may arise from changes to biological communities following shifts in climate (eg Threatened Species Legislation). There is likely to be a range of local, State and National legislation and policy challenges that are likely to arise and which need to be addressed (Kenchington & Warner, 2012).

10. Adaptation planning and implementation

The development of adaptation strategies to reduce the risks related to climate change in marine ecosystems and human communities and industries should be an integral part of the research needs outlined above. However, the advancement of adaptation theory and practice is in itself a science need. We need to improve understanding of the impacts of climate change on the services that the marine environment provides to marine industries and human communities, and to identify changes in practices, management and policy to foster ecological, social and economic adaptation to these changes, if necessary (FRDC, 2014). A particular need lies around identification and understanding of 'adaptation services', that is the range of services that emerge from biodiversity that can be managed to support the successful adaptation of human uses and activities (Williams *et al.*, 2012). Adaptation services include protection - where ecosystem services provide the 'scaffolding' to help withstand perturbations (such as mangroves reducing the impact of storm surges on coastal infrastructure), buffering – where ecosystem services provide resilience, through substitution, to ensure services continue under a range of possible futures, and options – where diversity in ecosystem composition supports flexibility in decision-making (i.e., provide choices). However, it is also important to understand the limits to adaptation in order to prioritise adaptation efforts and inform mitigation policy. Understanding the impacts and risks of climate change, and the risks of maladaptation, are addressed through approaches such as the development of 'adaptation pathways' that are robust to a range of a range of climate change scenarios (Fig. 3). There is a need to identify strategies and actions that can be pursued now, that will move towards climate-resilient pathways (IPCC, 2014). A focus is also needed to building the capacity of coastal communities and organisations, and marine "users", to adapt to climate change including responses to 'opportunities' that might arise, together with the identification of mechanisms and processes to implement adaptation options.

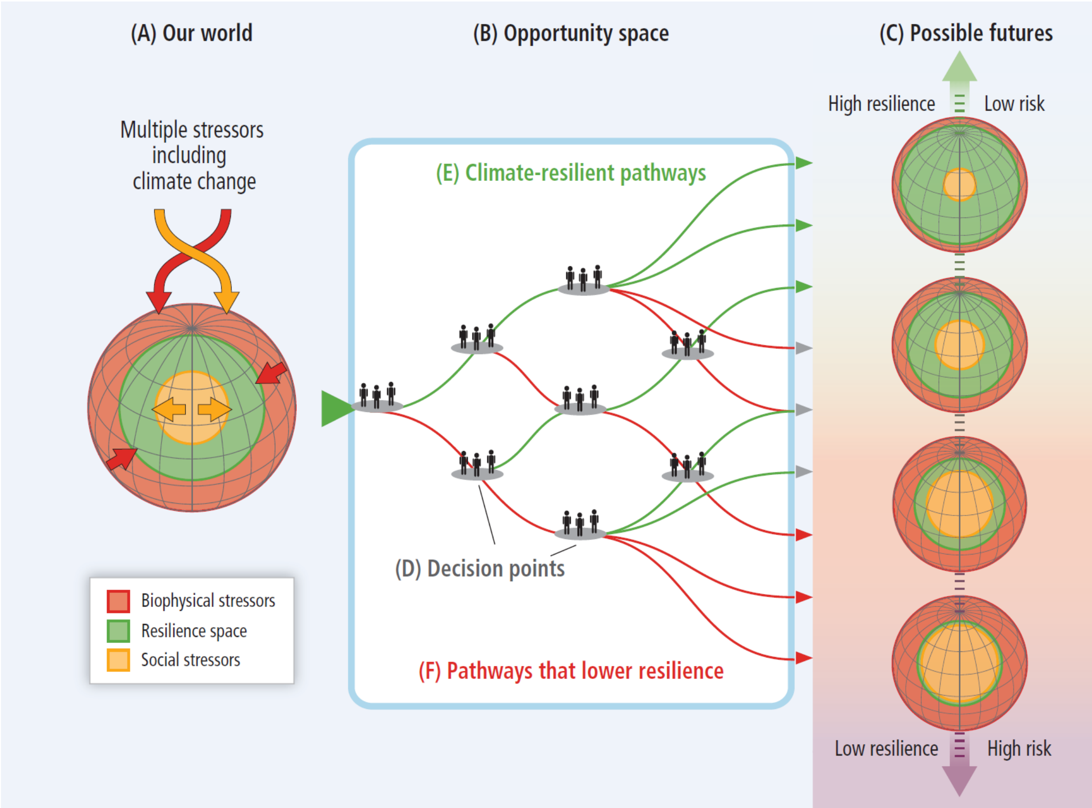

Figure 3. Opportunity space and climate-resilient pathways. (A) Our world is threatened by multiple stressors that impinge on resilience from many directions, represented here simply as biophysical and social stressors. Stressors include climate change, climate-variability, land-use change, degradation of ecosystems, poverty and inequality, and cultural factors. (B) Opportunity space refers to decision points and pathways that lead to a range of (C) possible futures with differing levels of resilience and risk. (D) Decision points result in actions or failures-to-act throughout the opportunity space, and together they constitute the process of managing of failing to manage risks related to climate change. (E) Climate-resilient pathways (in green) within the opportunity space lead to a more resilient world through adaptive learning, increasing scientific knowledge, effective adaptation and mitigation measures., and other choices that reduce risks. (F) Pathways that lower resilience (in red) can involve insufficient mitigation, maladaptation, failure to learn and use knowledge, and other actions that lower resilience; and they can be irreversible in terms of possible futures. From (IPCC, 2014)

Specific science priorities for the next 5, 10-20 years.

Within 5 years

- Improved understanding of how changes in the East Australian Current and Leeuwin Current affect regional marine ecosystems at seasonal, decadal and long-term time scales.
- Production of sets of regional scenarios for the physics, chemistry and primary productivity for Australian marine areas under climate change, and development to inform impact and adaptation research and marine management.
- Expand existing detailed inundation and extreme wave modelling (including collection of high resolution near-shore bathymetric and topographic information where unavailable.
- Improve understanding of future changes in sub-daily (1 – 12 hour) extreme rainfall events for high biodiversity coastal areas (e.g. the north Queensland coast).
- Develop and/or expand tools (and training) for rapid shoreline and coastal vulnerability assessments, in tropical northern Australia (and the region), i.e., Coral Triangle Initiative Map-Enhanced Decision Support (CTI-MEDS), Tools for Understanding Resilience to Fisheries (TURF).
- Improved marine forecasting of local phenomena, including ocean currents and eddies to allow climate variability to be accommodated in planning by marine managers and industries.
- Undertake climate change vulnerability and risk assessments for key species, ecosystems and marine industries and identify indicators for monitoring (e.g., Pecl *et al*., 2009, Pecl *et al.*, in press). Undertake research into physiological/behavioral responses and thresholds and capacity of acclimatization and genetic adaptation for key species. Assessments of the sensitivities of ecosystem function, goods and services to multiple stressors.
- Expand/maintain biological data collection in national and regional monitoring programmes to increase understanding of how inter-annual, decadal and long-term variability in climate affects marine ecosystems and primary production. Examples include monitoring for the impacts ocean acidification on calcifiers, extending monitoring of carbon chemistry and ecosystem impacts under IMOS, extending the geographic range and components of tidal wetland data collection, and data collection to inform understanding of the consequences of species distribution and phenology shifts. In particular, extend regional monitoring in shallow coastal and inshore systems.
- Extend the range of life stages and organisms investigated for their responses to climate change and ocean acidification in experiments and cover a range of climate zones (tropical to polar) Experiments and modeling to understand the relative importance of ocean (plankton) and coastal (seaweeds, seagrass, plankton) primary production for fisheries and the implications of future scenarios of primary production.
- Investigate the feasibility of using microbial indicators as rapid-assessment indices for ecosystem health that can be applied broadly on existing and planned physical monitoring infrastructure.
- Produce scenarios for how regional species patterns are expected to change, and identification of areas of rapid change and potential refugia.
- Application of modeling approaches to investigate the consequences of changing species distribution and phenology for ecosystem-based management and interactions with other ecosystem pressures.
- Collect empirical experimental data, and develop regional ecosystem models derived from these data to investigate relationships between nutrient availability, microbial populations and oxygen and pH concentrations under climate change scenarios and other pressures (e.g. fishing) the consequences for fisheries and whether system thresholds exist.

- Research into understanding the long-term impacts of extreme climatic events on ecosystems, including feedbacks and thresholds, on organisms and ecological processes.
- Undertake ecological, social and economic assessments of the risks from the impacts of climate change on marine ecosystems, including the consideration of climate change issues in fishery status reports. Integrated research to understand links between ecosystem function and economic/social impacts.
- Support integrated management and strategic assessments and planning. Review of management and governance of all sectors (in particular fisheries, conservation and tourism) to examine robustness to climate change and identify potential adaptation pathways.
- Establish programmes to assess the status and trends in ecosystem components and social and economic vulnerabilities as climate changes to increase understanding of the influences of inter-annual, decadal and longer-term climate variability.
- Establish/support mechanisms for the translation of science to conservation, management and policy planning. For example, extension of 5-yearly Outlook Report model of the Great Barrier Reef Marine Park Authority to other key Australian marine ecosystems, development of the Marine Report Card (Poloczanska *et al.*, 2012).
- Investigate implications for local, State and National legislation that may arise from changes in marine ecosystems, and the legal ramifications of such changes.
- Understanding of barriers to adaptation and integration of adaptation pathways and thresholds into management plans and policies.
- Development of decision-support tools for managers and policymakers to assist adaptation planning.
- Build a resource kit of possible adaptation responses that can be implemented by managers, if applicable, for the systems they manage. These can be derived from a range of current projects that consider responses to current weather/climate (e.g., the role that green zones played in increasing resilience of coral reefs in Moreton Bay following the 2011 floods (Olds *et al.*, 2014)).
- Build the capacity of coastal communities and organisations, and marine "users" to adapt to climate change including looking for opportunities which may arise. Build a vulnerability map for Australia's coastal marine and human systems.

Within 10-20 years

- Interdisciplinary monitoring and research program across physics, chemistry, ecology and social and economic indicators, across regional and local scales.
- Undertake ecophysiological experiments, including *in situ* experiments, with key species and mixed populations to increase understanding of responses, including evolutionary responses, and integrate with modeling studies. Expand understanding of ecosystem impacts through experiment work and in situ studies, especially novel manipulation approaches and comparative field experiments.
- Investigation of the impacts of changing temperature oxygen, and ocean pH and other stressors in combination on commercial fishes and shellfish, across all life stages. Integrate with regional models to inform management.
- Research program into the genetic and epi-genetic basis for adaptation to warming, ocean acidification and other stressors (both individually and in combination) for a broad range of key species, including commercial fish stocks.

- Environmental DNA-based monitoring of macro- and micro-organisms (i.e. establishing whether sampling DNA from the water column is a reliable representation of the animals and plants living in that habitat (including benthic organisms).
- Assessment of feasibility and risks of Assisted Evolution approaches stocks of marine organisms genetically enhanced for increased environmental stress tolerance
- Development of earth-system models that extend up the food web and integrate human activities and responses at a global scale.

Realisation

Key infrastructure and capability requirements/impediments

- Support and expand capability for climate change research, including atmospheric and oceanographic sciences, fundamental and applied ecological research, and economics and social science, to extend system understanding and produce solutions-based research outputs that support planning and decision-making. Establish programmes to facilitate multi-disciplinary collaboration.
- Ongoing commitment for sustained national collection, and platforms for delivery of, physical and chemical and biological variables through the Integrated Marine Observing System (IMOS). Support and extend development of IMOS science nodes and national program to address gaps in observing infrastructure and data collection (IMOS, 2014). Expansion geographical coverage into the coastal zone and develop programs of collection of biological data. Calibration of remote sensing products in coastal waters.
- Support regional contributions to *in situ* climate and oceanographic data collection including AIMS Automatic weather stations and sea temperature logger program, GBRMPA Marine Monitoring Program.
- Support and enhance regional ecological monitoring such as AIMS Long Term Monitoring Program in the Great Barrier Reef, GBRMPA Marine Monitoring Program, Rottnest Island tropical fish recruitment, fishery independent surveys (e.g., by Fisheries Queensland), and collection of data across the land and ocean systems.
- Enhance capability for biological data collection through support of high-quality citizen science programmes such as Redmap, Reeflife Survey, Eye on the Reef and ClimateWatch.
- Continued support for retrospective/historical monitoring using natural marine archives (e.g. AIMS coral core archive) to enhance availability of robust historical baseline information and indicators of key species performance and change (e.g., shifts in growth baselines, frequency of stress events and rates of recovery (Cantin & Lough, 2014)).
- Support experimental (both laboratory and field based) infrastructure around Australia such as AIMS SeaSim aquarium, SIMS, NMSC, university research stations, including facilities to investigate species adaptation and evolution.
- Support development of regional capability and contributions to regional and global work towards robust forecasts and projections of atmospheric and oceanic circulation and processes (e.g., Australian Global Climate Models (CSIRO and ACCESS), BLUElink, World Climate Research Programme CMIP).
- Development of capability for innovative modeling, communication and reporting tools for regional ecosystems (e.g., Atlantis, ereefs www.ereefs.org.au) to investigate ecological, economic and social ramifications of climate change impacts.

- Foster capability to develop innovative monitoring approaches (e.g., DNA-based monitoring) and solutions (e.g., genetically-enhanced stocks).
- Increase capability for adaptation research and the implementation of adaptation practices.

Funding and coordination requirements/impediments

- Funding programmes to arrest the loss of climate change science positions across the spectrum of research disciplines, hence expertise and capability, from Australia. Foster innovation through funding and support for fundamental science (e.g., through small and large competitive grant programs) and collaboration (e.g., such as the successful USA model for working groups at National Centre for Ecological Analysis and Synthesis (Hampton and Parker 2011)) as well as research flagships and science hubs.
- Continuing support for national programs of sustained monitoring of climatic, terrestrial, oceanographic and ecological variables and their coordination with international programs. For example, IMOS and its coordination with the sustained observations and ongoing development of the Global Ocean Observing System (GOOS), a permanent global system for observations, modeling and analysis of marine and ocean variables (www.ioc-goos.org).
- Establish a national, coordinated network of field stations and laboratories for investigation of climate change, ocean acidification and other impacts on species and ecosystems, and support to coordinate comparable experimental studies across latitudes. Provide support for collaborations using national facilities such as AIMS SeaSim aquarium.
- Increased scientific and fisheries engagement in major regional marine science, climate change, fisheries and food security initiatives. (i.e., CTI-CFF, ATSEA). CTI-CFF – currently Department of Sustainability, Environment, Water, Population and Communities is the lead AG agency for this major regional marine program – but there is a critical need for much stronger engagement with Australia's science and fisheries agencies and development agencies (DFAT, ACIAR, AusAID).
- Support for Earth System Science research, which addresses biophysical boundaries of the planet, recognizes that environmental changes can occur at global scales and/or have global impacts. These global issues, including climate change need to be addressed by integrated interdisciplinary studies and model development to find globally integrated solutions (Gifford *et al.*, 2010).
- Support participation in international research priorities and policy-relevant research goals, and regional and global coordination of climate change research and communication e.g., global coordination of blue carbon and ocean acidification research, contributions to the assessments and reports of Intergovernmental Panel on Climate Change and assessments and plans of the Convention on Biological Diversity.
- National coordination of science priorities and research through e.g., NCCARF, FRDC and CSIRO Flagships, while allowing for innovation outside these priorities (e.g. through blue-skies competitive grants program).
- Support policy- and management-relevant national reporting and communication such as State of the Environment, Marine Climate Change and Adaptation Report Cards.
- Coordinate adaptation research and the integration of research into adaptation planning for industry and communities (through CSIRO flagships, NCCARF, FRDC, The Great Barrier Reef Climate Change Adaptation Strategy and Action Plan).

References

Australian Bureau of Meteorology & CSIRO (2011) Climate Change in the Pacific: Scientific Assessment and New Research. Volume 1: Regional Overview. In: In. Pacific-Australia Climate Change Science and Adaptation Planning Program Technical Report, Melbourne, Australia.

Australian Bureau of Meteorology & CSIRO (2014) Climate Variability, Extremes and Change in the Western Tropical Pacific: new Science and Updated Country Reports. In. Pacific-Australia Climate Change Science and Adaptation Planning Program Technical Report, Melbourne, Australia.

Bates, A.E., Pecl, G.T., Frusher, S., Hobday, A.J., Wernberg, T., Smale, D.A., Dulvy, N., Edgar, G.J., Feng, M., Fulton, E.A., Hill, N., Holbrook, N.J., Radford, B., Slawinski, D., Sunday, J.M., Thompson, P.A. and Watson, R. (2014). Evaluating pathways of geographic range extensions and contractions. *Global Environmental Change* 26, 27–38.

Bell, J.D., Johnson, J.E. and Hobday, A.J. (eds) (2011a) *Vulnerability of tropical Pacific fisheries and aquaculture to climate change*. Secretariat of the Pacific Community, Noumea, New Caledonia.

Bell, J.D., Reid, C., Batty, M.J., Allison, E.A., Lehodey, P., Rodwell, L., Pickering, T.D., Gillett, R., Johnson, J.E., Hobday, A.J. and Demmke, A. (2011b) Implications of climate change for contributions by fisheries and aquaculture to Pacific Island economies and communities. *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change* (ed. by J.D. Bell, J.E. Johnson and A.J. Hobday). Secretariat of the Pacific Community, Noumea, New Caledonia.

Boyd, P.W. (2013) Framing biological responses to a changing ocean. *Nature Climate Change* 3, 530-533.

Brown, C.J., Fulton, E.A., Hobday, A.J., Matear, R., Possingham, H.P., Bulman, C., Christensen, V., Forrest, R., Gehrke, P., Gribble, N., Griffiths, S.P., Lozano-Montes, H., Martin, J.M., Metcalf, S.J., Okey, T.A., Watson, R. and Richardson, A.J. (2009) Effects of climate-driven primary production change on marine food webs: implications for fisheries and conservation. *Global Change Biology* **16**(4): 1194 – 1212.

Burkett, V.R., Suarez, A.G., Bindi, M., Conde, C., Mukerji, R., Prather, M.J., Clair, A.L.S. and Yohe, G.W. (2014) Point of departure. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* (ed. by C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. Maccracken, P.R. Mastrandrea and L.L. White). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Burrows, M.T., Schoeman, D.S., Richardson, A.J., Molinos, J.G., Hoffmann, A., Buckley, L.B., Moore, P.J., Brown, C.J., Bruno, J.F., Duarte, C.M., Halpern, B.S., Hoegh-Guldberg, O., Kappel, C.V., Kiessling, W., O'Connor, M.I., Pandolfi, J.M., Parmesan, C., Sydeman, W., Ferrier, S., Williams, K.J. and Poloczanska, E.S. (2014) Geographical limits to species-range shifts are suggested by climate velocity. *Nature*, **507**, 492-495.

Byrne, M. (2011) Impact of ocean warming and ocean acidification on marine invertebrate life history stages: vulnerabilities an potential for persistence in a changing ocean. *Oceanography and Marine Biology An Annual Review* 49: 1-42.

Byrne, M. and Przeslawski, R. (2013) Multistressor studies of the impacts of warming and acidification of the ocean on marine invertebrates' life histories. *Integrative and Comparative Biology* 53: 582-596.

Cantin, N.E. and Lough, J.M. (2014) Surviving coral bleaching events: *Porites* growth anomalies on the Great Barrier Reef. *PLoS ONE* 9, e88720.

CBD (2014) *An updated synthesis of the impacts of ocean acidifcation on marine biodiversity* (eds. S. Hennige, J.M. Roberts and P. Williamson), Secretariat of the Convention of Biological Diversity, Montreal, Canada. p. 99.

Cheung, W.W.L., Dunne, J., Sarmiento, J.L. and Pauly, D. (2011) Integrating ecophysiology and plankton dynamics into projected maximum fisheries catch potential under climate change in the Northeast Atlantic. *Ices Journal of Marine Science* 68, 1008-1018.

Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L., Kearney, K., Watson, R., Zeller, D. and Pauly, D. (2010) Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Global Change Biology* 16, 24-35.

Connell, S.D., Kroeker, K.J., Fabricius, K.E., Kline, D.I. and Russell, B.D. (2013) The other ocean acidification problem: CO_2 as a resource among competitors for ecosystem dominance. *Philosophical Transactions of the Royal Society B-Biological Sciences* 368: 1471-2970.

CSIRO an Australian Bureau of Meteorology (2014) *State of the Climate 2014*. Melbourne, Australia.

CSIRO & Australian Bureau of Meteorology (In press) *Climate Change in Australia Projections for Australia's Natural Resource Management Regions*: Technical Report. CSIRO and the Bureau of Meteorology, Melbourne, Australia.

DCCEE (2012) *A plan for implementing climate change science in Australia*. Department of Climate Change and Energy Efficiency, Canberra, Australia.

DEWHA (2010) *Australia's research priorities for cetaceans*. Department of the Environment, Water, Heritage and the Arts, Canberra, Australia.

Fabricius, K.E., Langdon, C., Uthicke, S., Humphrey, C., Noonan, S., De'ath, G., Okazaki, R., Muehllehner, N., Glas, M.S. and Lough, J.M. (2011) Losers and winners in coral reefs acclimatized to elevated carbon dioxide concentrations. *Nature Climate Change* 1: 165-169.

FRDC (2014) *Marine Australia. Directions for management and further research building on the findings for the Climate Change Adaptation - Marine Biodiversity and Fisheries R&D initiative*. Fisheries Research and Development Corporation.

Fulton, E.A. (2011). Interesting times: winners, losers, and system shifts under climate change around Australia. *ICES Journal of Marine Science* **68(**6): 1329-1342.

GBRMPA (2014) *Great Barrier Reef Outlook Report 2014*. Great Barrier Reef Marine Park Authority, Townsville, Australia.

Gifford, R.M., Steffen, W. and Finnigan, J.J. (2010) *To live within Earth's limits: An Australian plan to develop a science of the whole Earth system*. Australian Academy of Science, Canberra, Australia. 86pp.

Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C.V., Micheli, F., D'Agrosa, C., Bruno, J., Casey, K.S., Ebert, C., Fox, H.E., Fujita, R., Heinemann, D., Lenihan, H.S., Madin, E.M.P., Perry, M., Selig, E., Spalding, M., Steneck, R. and Watson, R. (2008) A global map of human impact on marine ecosystems. *Science* 319: 948-952.

Hampton, S.E. and Parker, J.N. (2011) Collaboration and productivity in scientific synthesis. *BioScience* 61(11): 900-910.

Helm, K.P., Bindoff, N.L. and Church, J.A. (2011) Observed decreases in oxygen content of the global ocean. *Geophysical Research Letters* 38 L23602.

Hobday, A.J., Chambers, L.E., Arnould, J.P.Y., Patterson, T.A., Wilcox, C., Tuck, G.N. and Thomson R.B. (2014). *Developing adaptation options for seabirds and marine mammals impacted by climate change*. Final Report. FRDC-DCCEE Marine National Adaptation Research Project 2010/0533.

Hobday, A.J. and Evans, K. (2013). Detecting climate impacts with oceanic fish and fisheries data. *Climatic Change* 119: 49–62.

Hobday, A.J., Hartog, J.R., Spillman, C.M. and Alves, O. (2011) Seasonal forecasting of tuna habitat for dynamic spatial management. *Canadian Journal of Fisheries and Aquatic Sciences* 68, 898-911.

Hodgkinson, J.A., Hobday A.J. and Pinkard, E.A. (2014) Climate adaptation in Australia's resource-extraction industries: ready or not? *Regional Environmental Change* 14(4): 1663-1678.

Hoegh-Guldberg, O., Cai, R., Poloczanska, E.S., Brewer, P.G., Sundby, S., Hilmi, K., Fabry, V.J. & Jung, S. (2014) The Ocean. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* (ed. by V.R. Barros, C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. Maccracken, P.R. Mastrandrea and L.L. White). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Holbrook, N.J. and Johnson, J.E. (2014). Climate change impacts and adaptation of commercial marine fisheries in Australia: a review of the science. *Climatic Change*. DOI 10.1007/s10584-014-1110-7

IMOS (2014) *Draft: National Science and Implementation Plan 2015-25*. imos.org.au/plansreports.

IPCC (2013) Summary for Policymakers. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. by T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley), pp. 1–30. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2014) Summary for Policymakers. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. by C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. Maccracken, P.R. Mastrandrea and L.L. White), pp. 1-32. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA.

Johnson, J.E. and Marshall, P.A. (eds) (2007) *Climate change and the Great Barrier Reef. A vulnerability assessment*. Great Barrier Reef Marine Park Authority and Australian Greenhouse Office, Australia.

Kenchington, R. and Warner, R. (2012) Uncertain seas ahead: legal and policy approaches to conserving marine biodiversity in the face of a changing climate. *Climate Change and the Oceans; Gauging the Legal and Policy Currents in the Asia Pacific and Beyond* (ed. R. Warner and C. Schofield), pp. 153-166. Edward Elgar Publishing, Cheltenham, UK; Northampton, MA, USA.

Kroeker, K.J., Michelia, F., Gambib, M.C. and Martz, T.R. (2011) Divergent ecosystem responses within a benthic marine community to ocean acidification. *Proceedings of the National Academy of Sciences of the USA* 108L 14515–14520.

Kroeker, K.J., Kordas, R.L., Crim, R., Hendriks, I.E., Ramajo, L., Singh, G.S., Duarte, C.M. and Gattuso, J.P. (2013) Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. *Global Change Biology* 19: 1884-1896.

Lim-Camacho, L., Hobday, A.J., Bustamante, R.H., Farmery, A., Fleming, A., Frusher, S., Green, B. S., Norman-Lopez, A., Pecl, G., Plaganyi, E.E., Schrobback, P., Thebaud, O., Thomas, L. and van Putten, E.I. (2014). Facing the wave of change: Stakeholder perspectives on climate adaptation for Australian seafood supply chains. *Regional Environmental Change* DOI 10.1007/s10113-014-0670-4.

Madin, E.M.P., Ban, N.C., Doubleday, Z.A., Holmes, T.H., Pecl, G.T. and Smith, F. (2012) Socio-economic and management implications of range-shifting species in marine systems. *Global Environmental Change-Human and Policy Dimensions*, 22, 137-146.

Marshall, N.A., Tobin, R.C., Marshall, P.A., Gooch, M. and Hobday, A.J (2013) Vulnerability of marine resource users to extreme weather events. *Ecosystems* 16(5): 797-809.

McLeod, E., Chmura, G.L., Bouillon, S., Salm, R., Björk, M., Duarte, C.M., Lovelock, C.E., Schlesinger, W.H. and Silliman, B.R. (2011) A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. *Frontiers in Ecology and the Environment* 9, 552-560.

Munday, P.L., Warner, R.R., Monro, K., Pandolfi, J.M. and Marshall, D.J. (2013) Predicting evolutionary responses to climate change in the sea. *Ecology Letters* 16, 1488-1500.

Munday, P.L., Cheal, A.J., Dixson, D.L., Rummer, J.L. and Fabricius, K.E. (2014) Behavioral impairment in reef fishes caused by ocean acidification at CO_2 seeps. *Nature Climate Change* 4:487-492.

O'Connor, M.I., Holding, J.M., Kappel, C.V., Duarte, C.M., Brander, K., Brown, C.J., Bruno, J.F., Buckley, L., Burrows, M.T., Halpern, B.S., Kiessling, W., Moore, P., Pandolfi, J.M., Parmesan, C., Poloczanska, E.S., Schoeman, D.S., Sydeman, W.J. and Richardson, A.J.

(2014) Strengthening confidence in climate change impact science. *Global Ecology and Biogeography*, DOI: 10.1111/geb.12218

Olds, A.D., Pitt, K.A., Maxwell, P.S., Babcock, R.C., Rissik, D. and Connolly, R.M. (2014) Marine reserves help coastal ecosystems cope with extreme weather. *Global Change Biology* 20, 3050-3058.

Parmesan, C. (2006) Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology Evolution and Systematics* 37: 637-669.

Parmesan, C., Burrows, M.T., Duarte, C.M., Poloczanska, E.S., Richardson, A.J., Schoeman, D.S. and Singer, M.C. (2013) Beyond climate change attribution in conservation and ecological research. *Ecology Letters* 16, 58-71.

Pecl, G.T., Ward, T., Doubleday, Z., Clarke, S., Day, J., Dixon, C., Frusher, S., Gibbs, P., Hobday, A., Hutchinson, N., Jennings, S., Jones, K., Li, X., Spooner, D. and Stoklosa, R. (in press). Rapid assessment of fisheries species sensitivity to climate change in south east Australia. *Climatic Change*.

Pecl, G., Frusher, S., Gardner, C., Haward, M., Hobday, A., Jennings, S., Nursey-Bray, M., Punt, A., Revill, H. and van Putten, I. (2009). *The east coast Tasmanian rock lobster fishery – vulnerability to climate change impacts and adaptation response options*. Report to Dept of Climate Change, Australia.

Pecl, G.T., Ward, T., Briceño, F., Fowler, A., Frusher, S., Gardner, C., Hamer, P., Hartmann, K., Hartog, J., Hobday, A., Hoshino, E., Jennings, S., Le Bouhellec, B., Linnane, A., Marzloff, M., Mayfield, S., Mundy, C., Ogier, E., Sullivan, A., Tracey, S., Tuck, G. and Wayte, S. (2014). *Preparing fisheries for climate change: identifying adaptation options for four key fisheries in South Eastern Australia*. Fisheries Research and Development Corporation, Project 2011/039.

Plagányi, E.E., Skewes, T.D., Dowling, N.A. and Haddon, M. (2013). Risk management tools for sustainable fisheries management under changing climate: a sea cucumber example. *Climatic Change* 119: 181-197.

Plaganyi, E.E., van Putten, E.I., Thebaud, O., Hobday, A.J., Innes, J., Lim-Camacho, L., Norman-Lopez, A., Bustamante, R.H., Farmery, A., Fleming, A., Frusher, S., Green, B.S., Hoshino, E., Jennings, S., Pecl, G., Pascoe, S., Schrobback, P. and Thomas, L. (2014). A quantitative metric to identify critical elements within seafood supply networks. *PLoS ONE* 9(3): doi:10.1371/journal.pone.0091833.

Poloczanska, E., Hobday, A.J. and Richardson, A.J. (eds) (2009) *Report Card for Marine Climate Change for Australia: a detailed scientific assessment*. CSIRO, Brisbane, Australia.

Poloczanska, E., Hobday, A.J. and Richardson, A.J. (eds) (2012) *Marine Climate Change in Australia, Impacts and Adaptation Responses. 2012 Report Card*. CSIRO Brisbane, Australia.

Poloczanska, E.S., Hoegh-Guldberg, O., Cheung, W., Pörtner, H.O. and Burrows, M. (2014) Cross-chapter box on observed global responses of marine biogeography, abundance, and phenology to climate change. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* (ed. by C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. Maccracken, P.R. Mastrandrea and L.L. White). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Poloczanska, E.S., Babcock, R.C., Butler, A., Hobday, A., Hoegh-Guldberg, O., Kunz, T.J., Matear, R., Milton, D.A., Okey, T.A. and Richardson, A.J. (2007) Climate change and Australian marine life. *Oceanography and Marine Biology,* 45: 407-478.

Poloczanska, E.S., Brown, C.J., Sydeman, W.J., Kiessling, W., Schoeman, D.S., Moore, P.J., Brander, K., Bruno, J.F., Buckley, L.B., Burrows, M.T., Duarte, C.M., Halpern, B.S., Holding, J., Kappel, C.V., O'Connor, M.I., Pandolfi, J.M., Parmesan, C., Schwing, F., Thompson, S.A. and Richardson, A.J. (2013) Global imprint of climate change on marine life. *Nature Climate Change* 3, 919-925.

Redfern, J.V., McKenna, M.F., Moore, T.J., Calambokidis, J., Deangelis, M.L., Becker, E.A., Barlow, J., Forney, K.A., Fiedler, P.C. and Chivers, S.J. (2012) Assessing the risks of ships striking large whales in marine spatial planning. *Conservation Biology* 27, 292-302.

Reisinger, A., Kitching, R.L., Chiew, F., Hughes, L., Newton, P.C.D., Schuster, S.S., Tait, A. and Whetton, P. (2014) Australasia. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* (ed. by V.R. Barros, C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. Maccracken, P.R. Mastrandrea and L.L. White). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Tourism Research (2014) *Tourism update: Updated results of the "State of Industry 2013". March Quarter 2014*. Australian Government Austrade, Canberra.

Risbey, J.S., Pook, M.J., McIntosh, P.C., Wheeler, M.C. and Hendon, H.H. (2009) On the remote drivers of rainfall variability in Australia. *Monthly Weather Review*, 137, 3233-3253.

Salinger, M. J. and A. J. Hobday (2013). Safeguarding the future of oceanic fisheries under climate change depends on timely preparation. Climatic Change 119: 3-8.

Saunders, M.I., Leon, J.X., Callaghan, D.P., Roelfsema, C.M., Hamylton, S., Brown, C.J., Baldock, T., Golshani, A., Phinn, S.R., Lovelock, C.E., Hoegh-Guldberg, O., Woodroffe, C.D. and Mumby, P.J. (2014) Interdependency of tropical marine ecosystems in response to climate change. *Nature Climate Change*, 4, 724-729.

Schlacher, T.A., Dugan, J., Schoeman, D.S., Lastra, M., Jones, A., Scapini, F., McLachlan, A. and Defeo, O. (2007) Sandy beaches at the brink. *Diversity and Distributions*, 13, 556-560.

Schoeman, D.S., Schlacher, T.A. and Defeo, O. (2014) Climate-change impacts on sandy-beach biota: crossing a line in the sand. *Global Change Biology*, 20, 2383-2392.

Spillman, C.M. and Hobday, A.J. (2014) Dynamical seasonal forecasts aid salmon farm management in an ocean warming hotspot. *Climate Risk Management* 1: 25-38.

Steffen, W., Hunter, J. and Hughes, L. (2014) *Counting the costs: Climate change and coastal flooding*. Climate Council of Australia Ltd, pp83.

Stramma, L., Prince, E.D., Schmidtko, S., Luo, J., Hoolihan, J.P., Visbeck, M., Wallace, D.W.R., Brandt, P. and Körtzinger, A. (2012) Expansion of oxygen minimum zones may reduce available habitat for tropical pelagic fishes. *Nature Climate Change*, **2**, 33-37.

Ullman, R., Bilbao-Bastida, V. and Grimsditch, G. (2013) Including Blue Carbon in climate market mechanisms. *Ocean & Coastal Management*, 83, 15-18.

Wernberg, T., Smale, D.A. and Thomsen, M.S. (2012) A decade of climate change experiments on marine organisms: procedures, patterns and problems. *Global Change Biology*, 18, 1491-1498.

Wernberg, T., Smale, D.A., Tuya, F., Thomsen, M.S., Langlois, T.J., de Bettignies, T., Bennett, S. and Rousseaux, C.S. (2013) An extreme climatic event alters marine ecosystem structure in a global biodiversity hotspot. *Nature Climate Change*, 3, 78-82.

Williams, K.J., Dunlop, M., Bustamante, R.H., Murphy, H.T., Ferrier, S., Wise, R.M., Liedloff, A., Skewes, T., Harwood, T.D., Kroon, F., Williams, R.J., Joehnk, K., Crimp, S., Stafford-Smith, M., James, C. & Booth, T. (2012) Queensland's biodviersity under climate change: impacts and adaptation - a synthesis report. . In: *A Report prepared for the Queensland Government, Brisbane.*, Canberra, Australia.

Zinke, J., Rountrey, A., Feng, M., Xie, S.P., Dissard, D., Rankenburg, K., Lough, J.M. & McCulloch, M.T. (2014) Corals record long-term Leeuwin current variability including Ningaloo Niño/Niña since 1795. *Nat Commun*, **5**