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The Oceans 2015 Initiative, Part II

**An updated understanding of the observed
and projected impacts of ocean warming
and acidification on marine and coastal
socioeconomic activities/sectors**

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CHANGING OCEANS, HUMAN ACTIVITIES AT RISK

Between 1971 and 2010, the oceans have absorbed approximately 93% of the excess heat caused by global warming, leading to several major changes such as the increase in stratification, limitation in the circulation of nutrients from deep waters to the surface, and sea level rise. In addition, the oceans absorbed 26% of anthropogenic CO₂ emitted since the start of the Industrial Revolution, which resulted in ocean acidification. Together, these processes strongly affect marine and coastal species' geographic distribution, abundance, migration patterns and phenology. As a consequence of these complex environmental changes, marine and coastal human sectors (i.e., fisheries, aquaculture, coastal tourism and health) are in turn at risk. This report provides an updated synthesis of what the science tells us about such a risk, based upon IPCC AR5 (2013-2014) and published scientific articles and grey literature that have been published between July 2013 and April 2015.

POTENTIAL CASCADING IMPACTS ON COASTAL SOCIETIES

Although uncertainty remains strong, there is growing scientific evidence that ocean warming and acidification will affect key resources for societies through ecosystems services. For example, while AR5 indicated that coral reefs had little scope for adaptation, recent research has suggested that there may be some capacity for some coral species to recover from climatic hocks and bleaching events, and to acquire heat resistance through acclimatization. This will have huge implications on many coastal economies in the developing and developed countries. More generally, key sectors will be affected. For example, while the fish catch potential is expected to decrease at the global scale, it will show diversified trends at the regional scale as fish stocks have started shifting in latitudes or by depth. This will impact regional to local fisheries systems. Also, climate and acidification-related impacts to existing aquaculture are expected to be generally negative, with impacts varying by location, species, and aquaculture method. Such foresights however do not consider the potential for adaptation, which aims precisely to limit the impacts of changes in environmental conditions.

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This report is part of the Oceans 2015 Initiative, which aims to develop an impact scenario of ocean acidification and warming for oceans and coasts at the global scale, from chemical and physical processes to impacts on marine and coastal organisms and ecosystems, as well as on related human activities. The overarching objective of the Oceans 2015 Initiative is to provide the UNFCCC process and key stakeholders, ahead of COP21, with the best possible information on what to expect from current and future changes in the ocean.

This report specifically assesses the most relevant available science on the possible impacts of ocean warming and acidification on marine and coastal human sectors (i.e., fisheries, aquaculture, coastal tourism and health). While several chapters of IPCC AR5 of Working Groups I and II already synthesise the available science, many scientific articles and grey literature have been published between July 2013 (cut-off date for IPCC reports) and now. This report thus aims to incorporate this knowledge. The goal here is not to be exhaustive, i.e. integrate all the papers that have been published recently, but rather to include the ones that really bring new insights (either strengthening or contradicting IPCC's conclusions).

The main conclusions of this report are the following:

- There continues to be strong evidence that climate change will lead to a redistribution of benefits and losses at multiple scales, and across human and ecological systems.
- Empirical and theoretical evidence continues to support the occurrence of climate-induced range shifts of species and coastal marine ecosystems, which were reported with very high confidence in AR5.
- While AR5 indicated that coral reefs had little scope for adaptation, recent research has suggested that there may be some capacity for some

coral species to recover from climatic shocks and bleaching events, and to acquire heat resistance through acclimatization.

- Studies have increasingly explored synergistic interactions between different climatic drivers, and have found strong variability between impacts to species at different life stages.
- Observed and projected climate-induced impacts suggest that sustainable freshwater aquaculture may be more viable than wild-caught fisheries under climate change.
- There has been increased effort to characterize and value ecosystem services in the context of climate change, with specific relevance to ecosystem-based adaptation.

1. INTRODUCTION

1.1. Major findings from the IPCC's AR5 WGII

Working Group II (WGII) of the Intergovernmental Panel on Climate Change's (IPCC's) Fifth Assessment Report (AR5) synthesized research regarding observed and projected impacts of climate change on coastal human and ecological systems. As the first report to allocate a separate chapter to oceans, AR5 offered an updated synthesis of our knowledge regarding the interactions between climatic drivers and marine systems while improving our understanding of the roles played by humans in altering and responding to changes in ocean systems.

Key findings from AR5 focused primarily on the ecological implications of climate change (see Howes *et al.*, 2015), but endeavoured to comment on corresponding socioeconomic impacts and regional differences in vulnerability and adaptive

capacity. Global redistributions of marine species were highlighted, with both observations and projections supporting further poleward range shifts under future increases in ocean temperatures (Pörtner *et al.*, 2014; Poloczanska *et al.*, 2014). The degrees to which species can track changes in climate as well as the influence of multiple stressors on their capacities to respond remained uncertain (Poloczanska *et al.*, 2014). Net primary productivity (NPP) was projected to decrease moderately by 2100 in the open ocean under both low- and high-emission scenarios, paralleled by an increase in NPP at high latitudes and a decrease in the tropics (Boyd *et al.*, 2014). However, existing research provided limited evidence regarding the directionality and magnitude of changes in NPP across different regions and ecosystems (Boyd *et al.*, 2014). While acknowledged as a critical process influencing ecosystem productivity, the likelihood of climate-induced changes to major upwelling systems (i.e., increased or decreased upwelling) was still uncertain (Lluch-Cota *et al.*, 2014).

Regional impacts to coastal communities and sectors were addressed, with a predominant focus on impacts to fisheries. While AR5 projected that poleward range shifts would likely negatively impact tropical and subtropical communities that depend on these resources for food and economic security (*high confidence*) (Pörtner *et al.*, 2014), the degree to which different communities would be affected was not addressed in detail. The prominent threat of sea level rise and the vulnerability of low-lying coastal areas, islands, and polar regions to climate change were reconfirmed (Larsen *et al.*, 2014; Nurse *et al.*, 2014). The report indicated that fisheries and aquaculture production were likely to experience variable impacts depending on the region, with key adaptation options including maintaining important ecosystems, ensuring occupational flexibility, and developing early warning systems for extreme events (Pörtner *et al.*, 2014). Impacts to coastal tourism were addressed to a lesser extent, with examples including a poleward redistribution of tourism flow due to increased temperatures, loss of beaches through coastal erosion and sea level rise, and reduced water supplies (Wong *et al.*, 2014). Likewise, impacts to human health focused primarily on increased frequency of disease transmission and range expansion, deaths associated with storm surges and flooding, increased prevalence of harmful algal blooms (HABs), and reduced food and water security (Wong *et al.*, 2014) (Larsen *et al.*, 2014; Nurse *et al.*, 2014) (Pörtner *et al.*, 2014).

Emerging research included a scaling up from species- to ecosystem-based assessments (Pörtner *et al.*, 2014), and called for an improvement in the

resolution of global climate models to allow for downscaled projections that could aid policy decisions, particularly for small islands (Nurse *et al.*, 2014). Community size structures were projected to decrease under climate change, with reductions in maximum body sizes occurring due to increased temperatures and reduced oxygen supply (Cheung *et al.*, 2013a; Pörtner *et al.*, 2014). While the processes behind ocean acidification were well understood, comprehensive studies of biological, ecological and biogeochemical impacts were limited in AR5 (Gattuso *et al.*, 2014a). However, existing research suggested that impacts were likely to be both positive and negative, with severe impacts to calcifying organisms such as reef-building corals and bivalves, but with potential benefits for some vegetative habitats (e.g., seagrasses) (Gattuso *et al.*, 2014a). At the time of AR5, global estimates of observed or projected economic costs associated with ocean acidification were limited (Gattuso *et al.*, 2014a). Research regarding the capacity for different taxa to adapt or acclimate¹ to different drivers was still limited, with studies rarely addressing adaptation to multiple stressors over longer time series (Pörtner *et al.*, 2014).

AR5 highlighted the need for a better understanding of how human systems might be affected by, and respond to, climate-driven events. While socio-economic vulnerability was projected to be highest in tropical countries (Pörtner *et al.*, 2014), examples of successful adaptation for small island nations—beyond relocation—were limited (Nurse *et al.*, 2014). Moreover, assessments of the social and economic costs of adaptation options were seldom available (Nurse *et al.*, 2014), with relative costs of adaptation varying strongly between and within regions (*high confidence*) (Wong *et al.*, 2014). In particular, the report called attention to the capacity and necessity of the international community's participation in aiding developing

1. In IPCC AR5 WGII (See IPCC 2014, Glossary), acclimatization refers to change in functional or morphological traits occurring once or repeatedly (e.g., seasonally) during the lifetime of an individual organism in its natural environment. Through acclimatization the individual maintains performance across a range of environmental conditions. For a clear differentiation between findings in laboratory and field studies, the term acclimation is used in ecophysiology for the respective phenomena when observed in well-defined experimental settings. The term (adaptive) plasticity characterizes the generally limited scope of changes in phenotype that an individual can reach through the process of acclimatization. In contrast, adaptation refers to the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects.

nations and small island communities (Nurse *et al.*, 2014), and illustrated that impacts to developing nations were likely to be more severe than developed nations due to lower adaptive capacities and limited resources (*high confidence*) (Wong *et al.*, 2014). Particularly for polar communities, AR5 provided examples of adaptive practices implemented by rural and Indigenous communities, illustrating ways in which dynamic adaptation through traditional knowledge and livelihood diversification can increase the resilience of vulnerable communities (Larsen *et al.*, 2014). Ecosystem-based adaptation also featured strongly in the report as a potential option for responding to climate change, yet examples were too few and too recent to facilitate a comprehensive assessment of benefits and risks (Shaw *et al.*, 2014).

1.2. Key uncertainties remaining from AR5

The concluding statements from AR5 identified key uncertainties regarding potential climate-related impacts on coastal natural and human systems. In particular, AR5 highlighted a need for an updated understanding regarding the following aspects:

1. Ways in which climate-induced changes in the physiology and biogeography of an individual species may alter ecosystem structures, species interactions, and food webs (Pörtner *et al.*, 2014);
2. An improved understanding of climate sensitivity at the ecosystem level that considers multiple drivers (e.g., ocean warming, acidification, and hypoxia) and synergistic impacts (Pörtner *et al.*, 2014; Wong *et al.*, 2014);
3. The capacity for phenotypic and evolutionary adaptation over generations to respond to long-term climate change (Pörtner *et al.*, 2014);
4. Increased resolution of forecasted impacts and changes at national and ecosystem scales to fisheries food production and security, and potential adaptation responses (Portner *et al.*, 2014);
5. Climate-related impacts to other coastal sectors, such as tourism (Wong *et al.*, 2014) and aquaculture (Portner *et al.*, 2014);
6. Models of potential drivers of disease transmission in coastal regions (Wong *et al.*, 2014); and
7. Better integration and projection of future interactions between human and natural systems under climate change (Pörtner *et al.*, 2014; Larsen *et al.*, 2014), as well as improving our capacity to distinguish between human and climate drivers (Wong *et al.*, 2014).

Specific research gaps by region included a need for more long-term monitoring of climate-related impacts to Arctic communities and their health,

well-being, traditional livelihoods, and ways of life, as well as a more comprehensive assessment of their respective vulnerabilities and response capacities at local and regional levels (Larsen *et al.*, 2014). Scale also remains a critical issue for small island developing states (SIDS), with country-specific data and risk assessments required to inform socioeconomic decisions in response to climate-induced change (Nurse *et al.*, 2014). Moreover, projections for a broader range of climatic variables (e.g., rainfall and drought, wind direction and strength, tropical storms and wave climate, etc.) were lacking, while the socioeconomic impacts and potential adaptation options for SIDS are rarely known (Nurse *et al.*, 2014). More generally, including developed countries, better understanding on the interactions between climate (including ocean acidification) and non-climatic drivers such as pollution, agriculture and urbanization and their impacts on marine related sectors is needed to inform more effective adaptation measures that addresses multiple stressors. Critically, authors of AR5 noted that the practice of adaptation often exceeds the rate at which peer-reviewed research describing and examining these practices can be produced and disseminated (Noble *et al.*, 2014). Thus, our knowledge on the effectiveness of these adaptation practices lag behind their implementation.

1.3. Study objectives

The objective of this paper is to review existing knowledge published following AR5 and update our understanding of the observed and projected impacts of ocean warming and acidification on marine and coastal ecosystems to human societies. For specific concerns, the study also includes the consequences of sea level rise into the analysis with the aim of showing that other drivers need to be considered for a comprehensive understanding of the extent to which human systems are/will be threatened. To discuss the effects of ocean warming and acidification on each sector, we need to examine the impacts on marine organisms and ecosystems, and the implications for living marine resources. However, we do not intend to repeat the complementary study by Howes *et al.*, (2015) that focus specifically on the impacts on organisms, species and ecosystems. Thus, a review of ecological impacts that are relevant to fisheries is provided in section 3.1 on fisheries, and complementary insights are provided in the sections dealing with aquaculture (3.2), coastal tourism (3.3) and human health (3.4). The study is a global-scale assessment, and insights from regional studies are obtained when information is available. Assessments of future impacts focus on

the 21st century.

The report endeavours to highlight key developments with respect to our scientific understanding of the relationships between different anthropogenic and climatic drivers on marine and coastal ecosystems, as well as novel areas of research regarding socioeconomic impacts and adaptation and mitigation strategies. Lastly, the review calls attention to areas of agreement with, and points of departure from, AR5.

2. METHODOLOGY

A literature review of peer-reviewed scientific literature not included in the latest IPCC WGII AR5 was conducted in order to identify recent scientific developments with respect to our understanding of the impacts of greenhouse gas (GHG) emissions on marine and coastal ecosystems and communities. Relevant studies available to the authors were obtained by browsing issues published in applicable peer-reviewed journals between 1 January 2013 and 31 October 2014. Subsequent literature searches were conducted using Google Scholar with a combination of search terms (see Table 1), specifying the appropriate dates of publication.

Table 1. Search terms used in the literature review.

SEARCH TERMS
"climate change" AND ('coast*' OR 'marine' OR 'fish*'); "climate change" AND 'aquaculture' OR 'mariculture'; "climate change" AND 'coast*' AND 'touris*'; "climate change" AND 'health' AND 'coast*'; "climate change" AND 'marine' AND 'polar'; "climate change" AND 'marine' AND 'tropical'; "climate change" AND 'coral'; "climate change" AND 'seagrass'; "climate change" AND 'marine' AND 'disease'; "climate change" AND 'polar' AND 'fish*'; "climate change" AND 'coast*' AND 'econ*'; "climate change" AND 'coast*' AND 'adapt*'; "climate change" AND 'marine' AND "ecosystem service"; "climate change" AND 'marine' AND 'fish*' AND 'policy'; "climate change" AND 'upwell*' AND 'fish*'; "climate change" AND 'fish*' AND 'adapt*'; "climate change" AND 'marine' AND "primary prod*"; "climate change" AND "marine" AND (oxygen* OR hypoxi* OR "dead zones" OR OMZ)

This review endeavours to capture corroborating, conflicting, and novel findings regarding the ecological and socio-economic impacts of climate change across a broad selection of geographical locations and sectorial divisions involved in coastal activities. The literature review was guided by the questions outlined in Table 2.

Table 2. Questions used to guide the literature review.

TOPIC	QUESTIONS
Fisheries	3.1.1 How are climate change drivers expected to impact fish stocks (distribution, composition, quantity of individuals, etc.) that are currently exploited?
	3.1.2 How are these changes expected to vary by ecosystem and geographical region?
	3.1.3 How are these impacts expected to affect fisheries' catch potential?
	3.1.4 What economic impacts are expected for fishing and auxiliary industries?
	3.1.5 How are these impacts expected to alter food security?
	3.1.6 What ramifications may arise with respect to multilateral business agreements (e.g., fishing in EEZs) and international agreements? What geopolitical impacts are likely to occur?
	3.1.7 What new evidence supports the theory of an emerging 'winners and losers' gap?
Aquaculture	3.2.1 How is climate change expected to impact future shellfish and fish aquaculture?
	3.2.2 What are the projected consequences of changes in aquaculture production on global food and economic security?
Coastal tourism	3.3.1 What are the consequences of ocean warming and acidification impacts on tourism flows?
	3.3.2 What are the consequences of ocean warming and acidification impacts on tourism operators' strategies?
	3.3.3 What are the economic consequences to be expected from ocean warming and acidification?
Human health	3.4.1 What are the possible impacts of climate-related drivers (e.g., diminished food and water security; extreme weather events; increased prevalence and transmission of disease) on human health?
Adaptation	3.5.1 What evidence exists of the capacity for coastal communities and sectors to mitigate and adapt to climate change?

3. SECTORS

This section develops the observed and projected impacts of ocean acidification and warming on four key sectors: fisheries (sub-section 3.1), aquaculture (3.2), coastal tourism (3.3) and human health (3.4). To allow a comprehensive understanding of what is at stake, each sub-section also synthesises information on the impacts of ocean acidification and warming on species and ecosystems that serve as “background conditions” for the studied sectors. Most of these environmental changes are presented in sub-section 3.1 on the fisheries sector, while complementary information is also provided in the other sub-sections.

3.1. Fisheries

3.1.1. How are climate change drivers expected to impact on ecosystems and its implications for fish stocks (distribution, composition, quantity of individuals, etc.) that are currently exploited?

Recent studies have sought to characterize how climate-related drivers alter species distributions and community size structures, with increased attention allocated towards synergistic effects, early developmental stages, and genetic and phenotypic adaptation. Additionally, indirect impacts to marine primary productivity have also been identified in relation to ocean warming and acidification. Key developments for each of these aspects will be addressed in turn, summarizing corroborating evidence and points of departure from the most recent IPCC report.

3.1.1.1. Climate velocity, range shifts and species assemblages

“Numerous observations over the last decades in all ocean basins show global-scale changes including large-scale distribution shifts of species (very high confidence) and altered ecosystem composition (high confidence) on multi-decadal time scales, tracking climate trends. The distribution and abundance of many fishes and invertebrates have shifted poleward and/or to deeper, cooler waters (high confidence)”

IPCC WGII AR5, Ocean Systems, Executive Summary, Pörtner et al., 2014; Box CC-MB, Poloczanska et al., 2014.

Warming-induced shifts in the abundance, geographic distribution, migration patterns, and phenology of species were reported and projected with *very high confidence* in the latest IPCC report (Pörtner et al., 2014). Empirical and theoretical evidence of range shifts in response to temperature gradients continues to emerge across various

taxa and many geographical locations (Poloczanska et al., 2013; Couce et al., 2013; Bates et al., 2014; Vergés et al., 2014), with observations supporting the hypothesis that range shifts correspond with the rate and directionality of climate shifts—or ‘climate velocity’—across landscapes (Loarie et al., 2009; Pinsky et al., 2013). In fact, variation in climate velocity was recently found to be a stronger predictor of the directionality and magnitude of taxon shifts than variations in life histories (Poloczanska et al., 2013, Pinsky et al., 2013).

Given this understanding, studies are now evaluating the degree to which taxa can track climate velocities and aiming to understand the factors that influence multi-dimensional range shifts (VanDerWal et al. 2013) and constrain range extension or contraction processes (Burrows et al., 2014, Bates et al., 2014). For instance, Feary et al., (2013) found that tropical fish species with large body size, high swimming ability, large size at settlement and pelagic spawning behavior were more successful at colonizing temperate habitats, while habitat and food limitation during juvenile stages may constrain movement. Conversely, Arctic and tropical fishes have been found occupying new habitats as temperature changes, further supporting the likelihood of poleward range shifts under ocean warming (Seth et al., 2013; Rummer et al., 2013). Observed range shifts associated with ocean warming are suggested to result in hybridization between native and invasive species through overlapping ranges, leading to reduced fitness and thus potentially increasing the risks of genetic extinction and reducing the adaptability to environmental changes (Muhlfeld et al., 2014; Potts et al., 2014). Some taxa are incapable of keeping pace with climate velocities, as observed with benthic invertebrates in the North Sea (Hiddink et al. 2014). Genetic bottlenecks can emerge where species exhibit limited dispersal capacity due to a lack of suitable habitat, thereby preventing population connectivity (e.g., lack of gene flow between populations of corkwing wrasse, *Symphodus melops*, in the North Sea and Portugal) (Knutsen et al., 2013).

More empirical evidence is now available that demonstrates the implications of species’ range shifts for the structure, functionality, and health of marine ecosystems. The tropicalization of temperate marine ecosystems through poleward range shifts of tropical fish grazers is shown to increase the grazing rate of temperate macroalgae such as in Japan and the Mediterranean (Vergés et al., 2014a). Such trophic impacts resulting from climate-induced range shifts are expected to affect ecosystem structure and dynamic in temperate reefs (Vergés et al., 2014b). Further evidence of community phase shifts from

coral-to algal- or sponge-dominated reefs has been linked to reductions in reef functionality and fisheries yield (Bell *et al.*, 2013b; Fang *et al.*, 2013; Ainsworth and Mumby 2014). Tropicalization events have already been witnessed in the Adriatic Sea, where invasive tropical jellyfish (*Pelagia noctiluca*) and three toxic dinoflagellate tropical species (*Ostreopsis lenticularis*, *Coolia monotis*, and *Prorocentrum mexicanum*) have been found (Marques *et al.*, 2014). Similarly, a heat wave event in western Australia was found to alter biodiversity patterns of temperate seaweeds (90% dieback), invertebrates, and demersal fish, leading to a tropicalization of community structure (Wernberg *et al.*, 2013; Thomson *et al.*, 2014). Range shifts in the urchin *Centrostephanus rodgersii* from New South Wales to Tasmania, Australia, have also been observed as a response to an increased influx of the East Australia Current (Johnson *et al.*, 2011). The urchin is thought to be responsible for the destruction of macroalgal habitat through grazing reducing habitat for black-lipped abalone and rock lobster, which has also been associated with changes in fish communities arising both from warming and habitat transformation (Johnson *et al.*, 2011). Subtropicalization of European pelagic fish communities has also been observed in the North Sea and Baltic Sea, with shifts from Atlantic herring and European sprat (1960s to 1980s) to Atlantic mackerel, Atlantic horse mackerel, European pilchard, and European anchovy (1990s onwards) in response to warming (Montero-Serra *et al.*, 2014). Phase shifts have been observed in polar regions: for example, macroalgal colonization of newly ice-free regions has recently occurred in Antarctica (Quartino *et al.*, 2013). In addition, the sensitivity of species' responses to ocean warming through range shifts is affected by ecosystem status: for example, increased reef community resilience to tropicalization has been observed through protection from fishing (Bates *et al.*, 2013).

3.1.1.2. Primary production

"From a global perspective, open ocean [net primary productivity] will decrease moderately by 2100 under both low- (SRES B1 or RCP4.5) and high-emission scenarios (*medium confidence*; SRES A2 or RCPs 6.0, 8.5, Sections 6.3.4, 6.5.1), paralleled by an increase in NPP at high latitudes and a decrease in the tropics (*medium confidence*). However, there is *limited evidence* and *low agreement* on the direction, magnitude and differences of a change of NPP in various ocean regions and coastal waters projected by 2100 (*low confidence*)."

IPCC WGII AR5, Box CC-PP, Boyd *et al.* 2014.

Similar to the findings from AR5, recent research continues to improve our understanding on the potential future changes in primary productivity. A common causative mechanism in models predicting such declines of global primary and export production is the increased stratification of the ocean in low- to mid-latitudes and a slowing of thermohaline circulation, reducing nutrient availability in surface water layers (Steinacher *et al.*, 2010). This is offset to some degree by reduction in sea ice at high latitudes leading to higher light availability and a reduction of temperature limitations to primary production. More recently models suggest an overall reduction in global primary production of 2 – 13% (Polovina *et al.*, 2011; Bopp *et al.*, 2013). Regardless of the current controversy in resolving whether ocean primary production has risen or fallen, it is clear that there are many unknown factors in predicting future trends. These arise from a lack of understanding of what drives interannual and multidecadal climatic variation (Chavez *et al.*, 2011), and the influence of species-specific responses to climate change effects (Chavez *et al.*, 2011).

Recent studies attempt to improve the ability to resolve projections of primary production in the coastal regions. In AR5, it was noted global projections of net primary production had poor representation for coastal ecosystems. Development of high-resolution shelf-seas lower-trophic-level ecosystem models contributes to improving the projection of net primary production in areas that are most important to fisheries (Barange *et al.*, 2014). Also, an increasing number of Earth System Models with ocean biogeochemical components explicitly include zooplankton in their model structure. Thus, projections of future changes in zooplankton production are available (e.g., Stock *et al.*, 2014). Zooplankton production and composition are important causal links to projecting future fisheries production.

3.1.1.3. Climate change and marine disease

Climate change has already begun to have impacts on outbreaks of disease in many marine organisms and even marine diseases that impact humans (see review in Burge *et al.*, 2014).

Warming has been shown to impair immune responses in host organisms, including shellfish (Travers *et al.*, 2009), corals (Harvell *et al.*, 2002), and finfish (reviewed in Bowden 2008). Recent reemergence of *Vibrio tubiashii*, a bacterial pathogen of larval Pacific oysters, was linked to warming and upwelling of low pH waters (Elston *et al.*, 2008). Disease impacts have shown a downside to adaptation to warming, as heat-resistant Pacific oysters were more resistant to an infection by a herpesvirus (Dégremont 2011).

Poleward shifts of diseases have impacted both humans and marine organisms, including bacterial infections of humans (Baker-Austin *et al.*, 2012; Martinez-Urtaza *et al.*, 2010) and disease in the eastern oyster, *Crassostrea virginica* (Burreson & Ragone Calvo, 1996; Ford & Tripp, 1996). Such impacts extend to tropical systems as well. For example, several coral diseases have increased with ocean warming (reviewed in Burge *et al.*, 2014). Due to robust thermal relationships with both winter and summer temperatures, some coral diseases are already being predicted using satellite SSTs (Heron *et al.*, 2010, Maynard *et al.*, 2011), and changes in disease outbreak events in future decades may be possible.

These links between climate change and marine diseases have had important ecosystem-level impacts (Burge *et al.*, 2014). Losses of over 50% of live coral cover after severe thermal stress and coral bleaching (Miller *et al.*, 2009; Eakin *et al.*, 2010) have dramatically altered the community composition of Caribbean coral reefs. Mass die-offs of eelgrass due to a wasting disease resulting from warmer conditions (Bockelmann *et al.*, 2013; Bull *et al.*, 2012) can cause a loss of key coastal habitats (Orth *et al.*, 2006; Waycott *et al.*, 2009). The loss of keystone predators, such as the ongoing dramatic die-off of sea stars along the Pacific coast of North America from a newly-identified densovirus (Hewson *et al.*, 2014), can dramatically change intertidal ecosystems (Paine 1969).

3.1.1.4. Community size structure and developmental stages

Recently, studies have highlighted the importance of assessing the impacts of climate-related drivers on community size structure (Woodworth-Jefcoats *et al.*, 2013) and on different stages of development, with particular emphasis on synergistic impacts (Hollowed *et al.*, 2013).

The relationships between climatic drivers, plankton community size structures, and trophic transfer efficiency have been studied extensively since the latest IPCC report. For instance, fish abundance has been found to be sensitive to changes in phytoplankton and zooplankton size structure, further strengthening the suggestion in AR5 that consideration of plankton size structure in addition to changes in primary productivity is necessary to accurately project ecosystem responses to climate change (Woodworth-Jefcoats *et al.*, 2013; Guenette *et al.*, 2014). While results from an *in situ* study suggest that ocean acidification may have a very limited impact on plankton assemblages under nutrient-depleted conditions, the resulting shift towards smaller, more heat-tolerant species (e.g., cyanobacteria) could lead to a reduction

in energy transfer to higher trophic levels, and synergistic effects through a combination of ocean warming and acidification could be unfavourable for cyanobacteria over longer time frames (Maugendre *et al.*, 2014). For instance, a study assessing the synergistic effects of temperate, nutrients and acidification on a coastal Norwegian food web projected similar shifts towards a new plankton community structure (i.e., autotrophic) and lower trophic transfer efficiency under multiple stressors (Calbet *et al.*, 2014), while a study in the Baltic Sea using data from 1979 to 2011 further corroborated a reduction in plankton community size structure and energy availability associated with warming and eutrophication (Suikkanen *et al.*, 2013).

“The warming-induced shifts in the abundance, geographic distribution, migration patterns, and timing of seasonal activities of species (*very high confidence*) have been and will be paralleled by a reduction in their maximum body size (*medium confidence*).”

IPCC WGII AR5, *Ocean Systems*, Pörtner *et al.* 2014.

As reported with *medium confidence* in the IPCC report (Pörtner *et al.*, 2014), smaller community size structures and reductions in body sizes have also been suggested by simulations of phase shifts between ecosystems (Ainsworth and Mumby 2014) and by projections of climate-related impacts to ecophysiology through reduced oxygen availability (Cheung *et al.*, 2013a). In a global study of pelagic communities, maximum body size and biomass were found to increase at high latitudes and to strongly decrease at low- to mid-latitudes in response to changes in metabolic requirements (Lefort *et al.*, 2014), which supports previous projections. Empirical evidence of reductions in body sizes have also been found for six of eight commercial fish species over a 40-year period in the North Sea, which coincided with a 1-2°C increase in water temperature and resulted in a 23% reduction of the mean yield-per-recruit (Baudron *et al.*, 2014). A reduced supply of nutrients due to greater stratification may also yield a reduction in the average size of phytoplankton and increase the number of trophic links within food webs, which in turn would reduce energy transfer efficiency (Bell *et al.*, 2013a).

Attention has also been given to climate-related impacts on taxa at early life stages, including the synergistic effects of ocean warming and acidification on sea urchin embryos (e.g., decreased developmental success under 2°C warming; Byrne *et al.*, 2013) and the impacts of ocean acidification on larval tropical fish (e.g., delayed development and reduced size-at-age for cobia [*Rachycentron*

canadum]; Bignami *et al.*, 2013). However, a recent literature review suggests that effects may vary largely between taxa, and that different levels of CO₂ could alter observed responses (Branch *et al.*, 2013). It is also important to note that the absence of a representative range of life stages could misrepresent a species' response to ocean acidification; for instance, earlier development stages of zooplankton have shown greater susceptibility to ocean acidification (Cripps *et al.*, 2014). In fact, the larval stage has been identified as a 'bottleneck' for survival in response to ocean acidification (Stumpp *et al.*, 2013; Byrne *et al.*, 2013). For instance, sea urchin larvae were found to be sensitive to ocean acidification, exhibiting reduced digestion efficiency and compensatory feeding (Stumpp *et al.*, 2013). Thus, failing to account for the full seasonal cycle and life history of a species can lead to 'blind spots' in vulnerability analyses, with potentially damaging consequences for conservation efforts and climate change mitigation (Small-Lorenz *et al.*, 2013).

3.1.1.5. Ocean acidification

In the IPCC's AR5, ocean acidification arising from climate change was projected with *high confidence* to exert negative effects on marine calcifiers and associated fisheries and aquaculture, yet existing studies failed to represent synergistic effects and produced observations seldom attributable to anthropogenic ocean acidification (Pörtner *et al.*, 2014).

"Impacts of ocean acidification range from changes in organismal physiology and behavior to population dynamics (*medium to high confidence*) and will affect marine ecosystems for centuries if emissions continue (*high confidence*)." *IPCC WGII AR5, Ocean Systems, Pörtner et al. 2014.*

Studies have since reported that ocean acidification has a significant negative effect on the survival, calcification, growth, development and abundance of marine taxa (Kroeker and Duarte 2013), and interacts synergistically with increased temperatures to reduce species tolerance (Wittmann and Pörtner 2013). For instance, Wittman and Pörtner (2013) quantified the proportion of species within taxa that are sensitive to a range of pH values—diverging from previous studies that had focused on individual species or aggregated taxa—and found evidence of sensitivity to ocean acidification across taxa (i.e., corals, echinoderms, molluscs, crustaceans, and fishes) and reduced tolerance to warming under elevated CO₂ levels. Modelled food web responses to ocean acidification indicate trophic cascades and contradictory

effects arising from changes in predator-prey dynamics: for instance, projected declines in copepod abundance in Puget Sound yield increases in microzooplankton (prey) and decreases in herring (predator) abundance, yet reduced macrozooplankton and euphausiid biomass release some pressure on copepods and, in turn, benefit herring (Busch *et al.*, 2013). While marine cyanobacteria, on the other hand, would likely increase their growth rates and their rate of nitrogen fixation in a high CO₂ world (Hutchins *et al.*, 2009), the process of nitrification by ammonia-oxidizing bacteria is negatively impacted by decreased pH (Beman *et al.*, 2011). A decrease in the generation of nitrate may lead to shift from NO₃⁻ to NH₄⁺, thereby favouring small-celled primary producers and disadvantaging large-celled organisms such as diatoms (Beman *et al.*, 2011), with subsequent effects on the biological carbon pump and the operation of marine food webs. Ocean acidification-induced changes in the flow of energy through—and dynamics of—food webs thereby illustrate the importance of key groups (e.g., copepods) to ecosystem structure and function (Busch *et al.*, 2013).

Studies have continued to corroborate the impacts of ocean acidification on calcifying organisms and the capacity of marine organisms to detect chemosensory cues, as recorded in AR5 (CC-OA, Gattuso *et al.*, 2014). While evidence suggests that adult fishes can survive high levels of CO₂ (Branch *et al.*, 2013), behavioural studies have found significant changes in species' responses under elevated levels of CO₂. In particular, ocean acidification has been found to impair a predator's capacity to detect prey (e.g., smooth dogfish, *Mustelus canis* (Dixson *et al.*, 2014b), and brown dottyback, *Pseudochromis fuscus* (Cripps *et al.*, 2011)) and fishes' abilities to respond correctly to olfactory and auditory cues warning of predation (e.g., two damselfish species—*Dascyllus aruanus* and *Pomacentrus moluccensis*—and two cardinalfishes, *Apogon cyanosoma* and *Cheilodipterus quinquelineatus* (Munday *et al.*, 2014); juvenile damselfish, *Pomacentrus amboinensis* (Ferrari *et al.*, 2012); and juvenile clownfish, *Amphiprion percula* (Simpson *et al.*, 2011)). These behavioural changes have been linked to increased activity of neurotransmitters (-aminobutyric acid, or GABA-A) that alter brain functioning under increased concentrations of CO₂, and which are prevalent in many invertebrate and vertebrate species (Branch *et al.*, 2013). This suggests that such responses may not be limited to a few species, and may therefore affect ecosystem dynamics.

Studies exploring species' resilience to ocean acidification suggest large variability between species (Range *et al.*, 2013) and functional groups

(Branch *et al.*, 2013). For instance, resilience to the synergistic impacts of ocean warming and acidification has been observed among juvenile sea urchins, yet conditions leading to shorter and weaker spines suggest increased vulnerability to predation (Wolfe *et al.*, 2013). Differing from previous studies, (Thomsen *et al.*, 2013) found that food availability outweighed the effects of ocean acidification on juvenile blue mussels (*Mytilus edulis*) in a eutrophic fjord in the Baltic Sea, which they attributed to high energy availability. However, subsequent analyses have found large variations between the sensitivities of different species and populations of juvenile and adult bivalves to climatic changes (Range *et al.*, 2013). Research on spider crabs (*Hyas araneus*), northern shrimp (*Pandalus borealis*), Antarctic krill (*Euphausia superba*), and European lobsters (*Homarus gammarus*) suggests that crustaceans—when compared with molluscs—are less severely impacted by exposure to higher concentrations of CO₂ (Branch *et al.*, 2013).

AR5 reported that ocean acidification might have a number of indirect effects on ocean primary production through stimulated production in seagrasses and growth in some phytoplankton (*high confidence*; Box CC-OA, Gattuso *et al.*, 2014a). However, a reduction in pH may also lead to a decrease in the bioavailability of iron, which can limit primary production (e.g., high-nutrient, low-chlorophyll regions such as the Southern Ocean, where primary production is largely limited by iron availability). A reduction in pH also has significant impacts on iron chemistry, affecting its speciation in seawater and reducing its availability to phytoplankton (Shi *et al.*, 2010). While the implications of this discovery are not entirely clear, they may indicate a positive feedback process (i.e., a weakening of the biological carbon pump as a result of acidification).

3.1.1.6. Deoxygenation and hypoxia²

Oxygen-depleted hypoxic conditions are now considered to be a major global environmental issue influenced by anthropogenic and climatic drivers, with particular relevance to tropical and temperate coastal systems (Bauer *et al.*, 2013). The oxygen levels of the ocean are maintained through the air-sea interface, where greatest concentrations are found at high latitudes where low temperatures lead to greater oxygen solubility in seawater (Keeling *et al.*, 2010). Oxygen is also generated in

the euphotic zone of the ocean through photosynthesis, and approximately tracks surface patterns of primary production (Keeling *et al.*, 2010). Extreme oxygen minimum zones (eOMZs; defined as oxygen levels less than 60 $\mu\text{mol kg}^{-1}$ (Thierry *et al.*, 2013)) develop where ocean circulation is weak and ventilation times are long (Karstensen *et al.*, 2008), creating conditions where many higher-trophic level species cannot survive. However, sensitivity to hypoxia differs greatly among taxa (Vacquer-Sunyer & Duarte 2008), with tolerance to low oxygen conditions also depending on temperature and CO₂ concentrations.

“The expansion of hypoxic regions termed Oxygen Minimum Zones (OMZs) and anoxic ‘dead’ zones, observed over the past 50 years and projected into the future under climate change, especially if combined with nutrient enrichment (eutrophication), will constrain the habitat of O₂-dependent organisms and benefit anaerobic microbes (*medium confidence*).”

IPCC WGII AR5, *Ocean Systems*, Pörtner *et al.* 2014.

Models predict a 1-7% decline in the oxygenation of the oceans by 2100 (reviewed in Keeling *et al.*, 2010), with a mean decline of 3.4% (1990-2090; Bopp *et al.*, 2013). Time-series observations in the Atlantic, Pacific, and Indian Oceans have shown declining oxygen levels since the 1950s (Keeling *et al.*, 2010; Gilly *et al.*, 2013). Declines in oxygen concentrations have been most severe in extreme oxygen minimum zones (eOMZs), with both vertical and horizontal increases in hypoxic waters (Pörtner *et al.*, 2014; Gilly *et al.*, 2013). For instance, since the 1960s, the maximum rate of declining oxygen levels at 200m depth has been $\sim 0.5 \mu\text{mol kg}^{-1} \text{yr}^{-1}$ in the Atlantic and tropical Pacific eOMZs (Stramma *et al.*, 2010). Long-term oxygen measurements in mid-water depths of the Gulf of Alaska and the Oyashio current off of Japan have shown a decrease of $\sim 7 \mu\text{mol kg}^{-1} \text{decade}^{-1}$ over the last 50 years (reviewed in Keeling *et al.*, 2010). Beyond eOMZs, levels of oxygen have declined at rates of $\sim 10\%$ of those cited for eOMZs (Gilly *et al.*, 2013). However, recent research has diverged from existing projections of expanding OMZs, arguing that a weakening of equatorial Pacific winds may lead to a contraction of anoxic conditions in the North Pacific despite the potential for a global, stratification-driven decline in O₂ supply (Deutsch *et al.*, 2014).

Both observed and projected changes in oxygen concentrations highlight the importance of understanding regional patterns, with evidence suggesting that observed trends in OMZs are linked to interdecadal regimes and variability in upwelling and trade wind strength (Deutsch *et al.*, 2014; Doney and Karnauskas 2014).

2. In ecological literature, the term hypoxia is commonly used for O₂ concentrations below 60 μ moles kg⁻¹, according to the transition to communities with characteristic hypoxia adaptations (Pörtner *et al.*, 2015).

Overall, it is likely that the expansion of eOMZs will lead to habitat compression and reduced abundance of species of pelagic and mesopelagic fish and zooplankton with low hypoxic tolerances. As observed off the coast of Oregon, where low oxygen conditions impinged on the continental shelf, groundfish and large crustaceans are likely to suffer increased rates of mortality (Chan *et al.*, 2008), potentially leading to a redistribution of species to more suitable habitat (Okey *et al.*, 2014). For diurnal vertical migrators, a “double squeeze” with respect to habitat availability may occur as a result of shoaling eOMZs and declining surface O₂ supply, with rising CO₂ levels potentially leading to hypercapnia (i.e., the interference of the exchange of oxygen between organisms and the environment) (Rosa and Seibel 2008, Seibel 2011). Collectively, this may restrict the depth of occurrence both from below (maximum depth) and above (shallowest depth) (Seibel 2011). For example, marlin found in the eastern tropical Atlantic between 1960 and 2010 were estimated to have experienced a 15% reduction in the volume of available habitat due to the shoaling of eOMZs (Stramma *et al.*, 2011). Other studies have corroborated this concern: in the Pacific, where OMZs are both expanding and shoaling, a shallower OMZ could reduce available vertical habitat within the water column and thereby detrimentally affect fishes with high oxygen demands (Hazen *et al.*, 2012). Moreover, a reduction in oxygen supply is expected to exacerbate reductions in the mean body sizes of fishes under warmer temperatures (Cheung *et al.*, 2013a). Conversely, the abundance of some species of hypoxia-tolerant organisms and cephalopods (e.g., Humboldt and jumbo squids) may increase (Stramma *et al.*, 2011). While the influence of eOMZs on biogeochemical cycling is difficult to predict, such zones may yield a change in the major groups of photosynthesizing organisms, with an increased occurrence of anoxygenic photosynthesizers (Gilly *et al.*, 2013).

3.1.1.7. Genetic and phenotypic adaptation

The capacity for species to acclimate or adapt to ocean acidification and other climatic drivers is still uncertain, but studies have increasingly explored the feasibility and implications of genetic and phenotypic responses.

While evolutionary adaptation to ocean acidification has been shown to be possible in principle, evolutionary trade-offs and temporal variability make it difficult to assess the degree to which adaptation can be deemed ‘successful’ (Sunday *et al.*, 2014). For instance, rapid transgenerational acclimation to increases in water temperature has been exhibited by reef fish (e.g., damselfish, *A. polyacanthus*) (Donelson *et al.*, 2011), while

the offspring of oysters exposed to elevated levels of CO₂ have been unaffected by these conditions (e.g., Sydney rock oysters, *Saccostrea glomerata*) (Parker *et al.*, 2012). Although this may suggest the capacity for species to mitigate climatic stressors through epigenetics (Branch *et al.*, 2013), such adaptation might come at the cost of other attributes or may be inhibited under multiple stressors (Donelson *et al.*, 2011). In particular, some forms of genetic adaptation may in fact be maladaptive (Merilä and Hendry 2014).

Historical and present-day environmental analogues have been used to assess the adaptation potential of marine taxa to environmental stressors (Munday *et al.*, 2013). For example, spatially-varying selection has been identified as a potential driver assisting with adaptation to ocean acidification among marine invertebrates by observing local conditions (Kelly *et al.*, 2013), while studies of the geological record and local environmental anomalies (e.g., CO₂ seeps) have allowed scientists to foreshadow future conditions and potential adaptations necessary for communities to survive (Munday *et al.*, 2013). However, some studies have recently argued that evidence of genetic adaptation is scarce, and that studies with better inferential methods are needed (Merilä and Hendry, 2014). Additionally, studies have recently demonstrated that some polar and tropical species are occupying the upper ranges of their thermal tolerances (Seth *et al.*, 2013; Rummer *et al.*, 2013), thereby supporting the hypothesis that vulnerability may be greatest for species in these regions due to narrow temperature tolerance ranges (*medium confidence*) (Pörtner *et al.*, 2014).

Evolutionary processes among zoo- and phytoplankton species in response to the synergistic effects of ocean warming and acidification are more poorly understood. However, a recent study of a globally important phytoplankton species—*Emiliania huxleyi*—suggests the capacity for the species to adapt to increased temperature in isolation (Schlüter *et al.*, 2014).

3.1.1.8. Scaling up to ecosystems and synergistic effects

As of AR5, synergistic effects in marine ecosystems had yet to be clearly detected and attributed in the field (Pörtner *et al.*, 2014). Simulated ecosystem-based assessments have continued to find theoretical evidence of phase shifts and trophic cascades in coral reef systems arising from synergistic effects associated with multiple stressors—such as deoxygenation, coral bleaching, ocean acidification, and disease—with projected declines in biodiversity and ecosystem services (Atweberhan *et al.*, 2013; Alva-Basurto and Arias-González, 2014).

“Interactions of temperature, ocean acidification, and hypoxia narrow thermal ranges and enhance sensitivity to temperature extremes in organisms such as corals, coralline algae, mollusks, crustaceans, and fishes (*high confidence*).”

IPCC WGII AR5, Ocean Systems, Pörtner et al. 2014.

Studies have increasingly scaled up to examine climate-related impacts on trophic interactions, or the synergistic impacts of multiple stressors. For instance, using a size-spectrum dynamic bioclimate envelope model (SS-DBEM), (Queirós *et al.*, 2014) found that the predatory behavior of a marine gastropod (*Nucella lapillus*) and its susceptibility to predators were detrimentally altered through ocean acidification, thereby providing a means of projecting impacts to trophic interactions accompanying climatic drivers. A recent study by Brown and Thatje (2014) found significant correlation between the hypoxia thresholds and hyperbaric thresholds of taxonomic groups, suggesting that the combined effects of temperature, pressure and oxygen concentration constrain the capacity of marine invertebrates and fishes to respond to changes in environmental conditions through range shifts. Their results corroborate previous projections that polar species are likely to be more vulnerable to climate change due to constrained ecological niches (e.g., Cheung *et al.*, 2009), and suggest that tropical and temperate fauna may experience substantial range expansion under the combined influence of ocean warming and deoxygenation (Brown and Thatje, 2014). In some locations, it is thought that hypoxia may function as a greater driver of poleward shifts than warming (e.g., poleward shifts of southern groundfish communities in the Pacific Northeast basin (Okey *et al.*, 2014)).

Importantly, synergistic effects have also been found to alter projected outcomes: for example, despite individual stressors leading to declines in production, a combination of increased temperature and nutrient loads was shown to increase zooplankton production and food web efficiency in a microcosm experiment conducted in Baltic Sea conditions (Lefébure *et al.*, 2013).

However, despite these recent developments, the projected outcomes of synergistic effects are still supported by experimental evidence.

3.1.1.9. Ocean upwelling zones

Just five upwelling zones, representing 5% of the ocean area are responsible for approximately 25% of world marine capture fisheries (Jennings *et al.*, 2001). Upwelling zones are particularly prone to climate change due to changes in the physical drivers of upwelling and accompanying changes in the supply of nutrients and oxygen (related to

temperature and surface/deep mixing); these, in turn, interact with the biological elements within the ecosystem.

“The climate-change-induced intensification of ocean upwelling in some eastern boundary systems, as observed in the last decades, may lead to regional cooling rather than warming of surface waters and cause enhanced productivity (*medium confidence*), but also enhanced hypoxia, acidification, and associated biomass reduction in fish and invertebrate stocks. Due to contradictory observations there is currently uncertainty about the future trends of major upwelling systems and how their drivers (enhanced productivity, acidification, and hypoxia) will shape ecosystem characteristics (*low confidence*).”

IPCC WGII AR5, Ocean Systems, Pörtner et al. 2014.

Stratification is projected to increase across most of the tropical Pacific, with synergistic interactions between temperature and salinity reinforcing stratification in the areas around the Pacific Warm Pool, South Pacific Convergence Zone (SPCZ), and intertropical converge zone (ITCZ) (Ganachaud *et al.*, 2013). Likewise, ensemble projections obtained from 36 of the models from the fifth Coupled Model Intercomparison Project (CMIP5) suggest a weakening of deep Southern Ocean convection associated with surface freshening and stratification under climate change, which in turn may reduce the production rate of Antarctic Bottom Waters and alter ocean heat and carbon storage processes (de Lavergne *et al.*, 2014). In addition, a recent meta-analysis of eastern-boundary upwelling regions shows that winds have intensified in the California, Benguela, and Humboldt systems but weakened in the Iberian system in the past decades (up to 60 years), with the intensity of change consistent with warming pattern (Sydeman *et al.*, 2014). This provides evidence to support the hypothesis of upwelling intensification in eastern boundary upwelling systems under climate change (Sydeman *et al.*, 2014). The implication of intensified upwelling on future fisheries is currently uncertain. On one hand, intensified upwelling may enhance nutrient supply, potentially increasing primary and fisheries production. On the other hand, it may also lead to increase in acidity and hypoxic conditions that would reduce fisheries production.

3.1.2. How are these changes expected to vary by ecosystem and geographical region?

3.1.2.1. Tropical marine ecosystems

The biophysical impacts of climate change and ocean acidification on tropical marine ecosystems—particularly coral reefs—were addressed

with great detail in the latest IPCC report (Box CC-CR, Gattuso *et al.*, 2014b). In particular, AR5 expressed *high confidence* that warming and acidification would lead to coral bleaching, mortality and decreased constructional ability, and argued that this made coral reefs the most vulnerable ecosystem to ocean warming and acidification with little scope for adaptation (Wong *et al.*, 2014). Having reached general consensus regarding the impacts of individual climate-related drivers on coral reefs (Chan and Connolly 2012; Ateweberhan *et al.*, 2013), studies now seek to understand the synergistic effects of multiple stressors on coral reef resilience (Mumby *et al.*, 2013, McClanahan *et al.*, 2014, Ban *et al.*, 2014), and the processes that influence reef adaptation and recovery (Roff *et al.*, 2014; Palumbi *et al.*, 2014; Dixon *et al.*, 2014a).

Some species of coral have since demonstrated the capacity to acquire heat resistance through acclimatization (Palumbi *et al.*, 2014) and to recover from bleaching events (Roff *et al.*, 2014). For example, changes in symbiotic communities from stress-sensitive to stress-tolerant symbionts following bleaching events can lead to increased thermo-tolerance among corals (Silverstein *et al.*, 2014). This has been supported by modelling studies indicating some adaptive responses have already resulted in higher thermal tolerances in some corals (Logan *et al.*, 2013). Recent projections suggest that biogeochemical responses of coral reef communities to ocean acidification could partially offset changes in seawater pH (12-24%) and the aragonite saturation state (15-31%) (Andersson *et al.*, 2014). In other cases, biofilm-induced larval settlement for coral reef sponges was found to exhibit higher settlement success among biofilm communities developed at higher seawater temperatures (e.g., *Rhopaloeides odorabile* in the Great Barrier Reef), suggesting groups that may be more resilient to increased temperatures under climate change; however, these results may be taxa-specific (Whalan and Webster, 2014). The inclusion of such adaptive responses (e.g., directional genetic selection, symbiont shuffling) in models is important for accurately predicting how ocean warming and acidification may affect coral reefs, with one such example reducing the frequency of mass bleaching events by 20 to 80% (scenario dependent) by 2100, compared with 'no adaptive response' projections (Logan *et al.*, 2013).

However, the capacity for recovery or adaptation is less certain if multiple stressors were to act in concert (Palumbi *et al.*, 2014). For instance, studies have shown that changes in water quality through nutrient loading and sedimentation can increase the severity of coral disease and bleaching (Vega Thurber *et al.*, 2013), while improved water quality

management can aid reef resilience and recovery (Gurney *et al.*, 2013). Other scientists have noted that observed changes in net ecosystem calcification could, in fact, be primarily due to increased dissolution of CaCO₃ rather than decreased calcification (Eyre *et al.*, 2014). Moreover, recent study on coral reef in Hawaii suggests that ocean acidification decreases calcification and increases reef erosion, making reefs increasingly susceptible to storm damage and sea-level rise (Silbiger *et al.*, 2014). Additionally, it has been recently noted that cumulative impacts of repeated bleaching events could lead corals with little or no phenotypic plasticity to become increasingly sensitive to bleaching, with responses to singular bleaching events being insufficient to gauge subsequent resilience (Grottoli *et al.*, 2014).

Coral reef structure and larval recruitment are expected to be altered due to synergistic drivers arising from ocean warming and acidification. Phase shifts from reef-building hard corals to non-reef-building soft corals have been suggested in tropical regions under increased ocean acidification (Inoue *et al.*, 2013). Rate of decalcification of patch-reefs in mesocosm has also been shown to increase substantially with increased CO₂ (Hoegh-Guldberg *et al.* 2007; Dove *et al.*, 2013). The implications of such loss of critical coral reef habitat are manifold: phase shifts to sponge reefs, for example, are expected to lead to reduced habitat complexity and biodiversity (Bell *et al.*, 2013b). Since chemical cues play critical roles in attracting coral larvae and juvenile fishes to healthy (coral-dominated) rather than degraded (seaweed-dominated) reefs, coral reef recovery may be constrained past a certain threshold (Dixon *et al.*, 2014a). A recent study also found evidence that pre-motile coral development in subtropical and temperate habitats may be restricted to a narrow temperature range, with an optimal temperature of 25°C irrespective of latitudinal differences (Keshavmurthy *et al.*, 2014). Climate-induced increases in ocean temperature and changes in planktonic food supply have also been synergistically linked to longer settlement times and decreased growth rates among larval reef fishes, with increased oxygen consumption rates (McLeod *et al.*, 2013). Synergistic effects may also reduce the quality and abundance of juvenile reef fish: for instance, while elevated CO₂ concentrations were found to stimulate reef fish reproduction (e.g., anemonefish, *Amphiprion melanopus* (Miller *et al.*, 2013b), subsequent analyses revealed that reproduction declined under elevated temperatures and that offspring quality suffered under elevated CO₂ conditions (Miller *et al.*, 2014).

Options for increasing coral reef resilience and improving conservation efforts have continued to emerge. While a global study of tropical reefs found no long-term refugia from the effects of both acidification and bleaching, with 90% of all locations expected to experience severe annual bleaching events by 2055 (van Hooidonk *et al.*, 2013b), temporary refugia have been identified in the western Indian Ocean, Thailand, the southern Great Barrier Reef, central Polynesia (van Hooidonk *et al.*, 2013a), and the Red Sea (Fine *et al.*, 2013). Such reef refugia have served to protect coral and fish biodiversity historically (e.g., in response to environmental shifts during the Quaternary period; Pellissier *et al.*, 2014). Therefore, prioritizing the protection of more resilient reefs to aid re-seeding efforts (e.g., shallow tropical reefs in the Indian Ocean (Freeman *et al.*, 2013) or maintaining reef refugia by mitigating GHG emissions (van Hooidonk *et al.*, 2013a)) may increase the potential for reefs to respond to climate change. The benefits of preserving ecosystem structure and predation have been illustrated through empirical evidence of increased resilience to climate-related drivers (e.g., protecting or restoring parrotfish grazing in the Caribbean increases resilience of coral reef habitats; Bozec *et al.*, 2014; Jackson *et al.*, 2014).

While studied to a lesser extent, shallow tropical water systems and coastal mangroves may undergo local (i.e., landward) and global (i.e., poleward) spatial shifts in response to climate-related drivers. Mangrove habitats are expected to respond to higher temperatures and CO₂ concentrations through poleward range shifts and faster growth rates, with species richness increasing at higher latitudes (Ross and Adam 2013). Southern and eastern range expansions have already been reported in Australia (Ross and Adam 2013). However, while a spatial analysis of Gazi Bay in Mombasa, Africa, suggests that coastal mangrove forests may be able to migrate landwards in response to lower scenarios of sea level rise (SLR), adaptation probabilities decrease under higher rates of SLR due to saline intrusion (Di Nitto *et al.*, 2014). Decreased growth rates under higher levels of salinity were further corroborated under other studies (Mitra, 2013). Species-specific adaptation is also influenced by interspecific competition and recruitment strength, which may alter community composition within mangrove forests (Di Nitto *et al.*, 2014). Thus, evidence of the capacity for coastal habitats such as salt marshes and mangroves to spatially respond to SLR is still considered inconclusive and site-specific (Spalding *et al.*, 2014). In the Atlantic, it has been predicted that warming will likely kill off kelp forests in the south, ocean

acidification will reduce calcifying algae in the north, and combined impacts of seawater warming, ocean acidification, and increased storminess may replace structurally diverse seaweed canopies with simple habitats dominated by noncalcified, turf-forming seaweeds (Brodie *et al.*, 2014). However, warming may limit the southern edge of eelgrass distributions as wasting disease has been shown to be associated with warmer seasons and locations (Bockelmann *et al.*, 2013; Bull *et al.*, 2012). In the Mediterranean Sea, distributions of some seagrasses such as *Zostera noltii* are projected to expand northward by 2100 (Valle *et al.*, 2014).

IPCC reported that the capacity for coastal ecosystems (e.g., mangroves, seagrasses, saltmarshes) to store and sequester carbon—otherwise known as ‘Blue Carbon’—provides opportunities to mitigate anthropogenic CO₂ emissions (*limited evidence, medium agreement*) (Hoegh-Guldberg *et al.*, 2014). Evidence that the preservation of coastal vegetative habitats and wetlands can yield a net uptake of atmospheric CO₂ has since been found in boreal, temperate, and subtropical seagrasses (Tokoro *et al.*, 2014), and agreement that coastal wetlands aid in regulating GHG emissions continues to accumulate (Ross and Adam 2013). However, recent research suggests that the magnitude of carbon storage can vary greatly by location (i.e., depth or latitude) and species (e.g., temperate and subtropical seagrasses in coastal Australia) (Lavery *et al.*, 2013).

In the context of coral reefs, Rogers *et al.* (2014) used a scenario-based approach to evaluate the sensitivity of 14 ecosystem services to different climate-related drivers and management strategies. While their research suggests that reserves will remain effective for reefs with high structural complexity, maximizing ecosystem services in degraded reefs would require a portfolio of management strategies (e.g., provision of artificial complexity, coral restoration, fish aggregation devices, herbivore management) (Rogers *et al.*, 2014).

3.1.2.2. Temperate and subtropical marine ecosystems

“Temperate seagrass and kelp ecosystems will decline with the increased frequency of heat waves and sea temperature extremes as well as through the impact of invasive subtropical species (*high confidence*).

IPCC WGII AR5, Coastal Systems and Low-Lying Areas, Wong et al. 2014.

Coastal vegetative habitats exhibit interdependence with coral reef ecosystems: for instance,

seagrasses function as nurseries for early life-stages reef fish and are, in turn, sheltered from incoming waves by coral reefs (Saunders *et al.*, 2014). This suggests that a climate- and CO₂- driven loss of coral reefs or other critical habitats may therefore have large-scale implications across ecosystems (Saunders *et al.*, 2014). Moreover, the importance of coastal lagoon ecosystems to fishing, aquaculture, tourism, and industrial sectors—particularly within the Mediterranean Sea—demonstrates how biophysical changes could yield detrimental socioeconomic impacts across sectors, thereby reducing local food and economic security (Marques *et al.*, 2013).

In situ mesocosms have been used to assess the synergistic impacts of CO₂ concentrations, nitrogen (N) availability, and relative sea levels on tidal marshes, and have found supporting evidence of increased plant growth associated with elevated CO₂ and N concentrations that could bolster resilience in response to sea level rise (Langley *et al.*, 2013). However, the complexity of synergistic effects could lead to phase shifts from stress-sensitive to stress-tolerant species, thereby jeopardizing tidal marsh community structure (Langley *et al.*, 2013). Similarly, elevated concentrations of CO₂ have been hypothesized to have the potential to offset detrimental effects of increased temperatures on seagrasses and macroalgae (Koch *et al.*, 2013).

As projected by Wong *et al.* (2014), temperature-mediated fish herbivory has been shown to detrimentally impact tropicalized temperate marine systems by preventing kelp ecosystems from recovering from climatic drivers (e.g., effect of overgrazing of kelp beds in southern Japan; Vergés *et al.*, 2014). Altered interspecific interactions between sympatric coastal fishes were observed in the Mediterranean under warmer conditions, with a cooler-water fish (e.g., rainbow wrasse, *Coris julis*) being displaced by a more dominant warmer-water fish (e.g., ornate wrasse, *Thalassoma pavo*) (Milazzo *et al.*, 2013). These examples support the theory that there will be ‘winners’ and ‘losers’ under climate change, with warm-adapted species outcompeting cold-adapted species in temperate marine ecosystems.

In the California Current system, there have been significant shifts in zooplankton communities as a result of temperature changes (e.g., Doney *et al.*, 2012), distributional shifts of coastal and oceanic fishes potentially associated with rising temperatures and changes in stratification (Hsieh *et al.*, 2009), and negative impacts to the abundance and condition of finfish and crustaceans (Keller *et al.*, 2010). Moreover, increased mortality has resulted from the impingement of hypoxic upwelled water

on shallow-water coastal ecosystems (Keller *et al.*, 2010), while mass-mortality events have been recorded in relation to hypoxic or anoxic events (see Chan *et al.*, 2008). Research modeling the influence of climate change in the North Pacific also identifies a substantial contraction of the temperate biome of the northeastern Pacific, which is projected to result in a ~38% decline in primary production for this region and, in turn, negatively impact fisheries and aquatic predators (Polovina *et al.*, 2011).

The Benguela Current ecosystem has shown dramatic changes in both the Southern and Northern regions. The Southern Benguela has shown large changes in abundance and size distribution of copepod populations (Verheye & Richardson, 1998), switches from anchovy to sardine dominance along with shifts in the distribution of both species (Cury & Shannon, 2004; Shannon *et al.*, 2004; Roy *et al.*, 2007; Crawford *et al.*, 2008) and large-scale shifts in the distribution of rock lobster populations with subsequent impacts on other elements of benthic communities (Cockcroft *et al.*, 2008). In the Northern Benguela region there have been successive changes in the pelagic ecosystem with a reduction of sardine abundance which was replaced by horse mackerel and mesopelagic species, followed by a decline of these species as well as decreases in aquatic predators (birds and seals (Cury & Shannon, 2004; Crawford *et al.*, 2008). Jellyfish may have become more abundant in the northern Benguela during these events (Crawford *et al.*, 2008).

3.1.2.3. Polar marine ecosystems

Discernible impacts attributed to climate change have been recorded in polar marine ecosystems, but studies evaluating these impacts remain scarce and primarily focus on species of economic importance (e.g., cod, shrimp) or marine mammals (Wassmann *et al.*, 2011; McBride *et al.*, 2014).

“Loss of sea ice in summer and increased ocean temperatures are expected to impact secondary pelagic production in some regions in the Arctic Ocean, with associated changes in the energy pathways within the marine ecosystem (*medium confidence*). These changes are expected to alter the species composition of zooplankton in some regions, with associated impacts on some fish and shellfish populations (*medium confidence*). {28.2.2.1} Also, changes in sea ice and the physical environment to the west of the Antarctic Peninsula are altering phytoplankton stocks and productivity, and krill (*high confidence*). {28.2.2.2}”

IPCC WGII AR5, Polar Regions, Larsen et al. 2014.

A loss of critical habitat (e.g., sea ice cover) has been projected to lead to an increase in genetic flow

and disease transfer between previously isolated populations of marine fauna (Post *et al.*, 2013), while a longer open-water season through decreased sea-ice cover could increase coastal erosion and storm impacts (Barnhart *et al.*, 2014). Recent research has provided new insight regarding the susceptibility of polar marine ecosystems to light-driven tipping points emerging from changes in ice loss and solar irradiance. In particular, areas without ice and snow following the summer solstice are particularly vulnerable to abrupt changes due to increased solar exposure through earlier ice loss; for this reason, future ice loss may lead to autotroph-dominated polar ecosystems with higher productivity, but lower regional biodiversity (Clark *et al.*, 2013).

As seen in the Mediterranean, increased temperature has been shown to affect the physiology and interspecific competition exhibited by Arctic fish fauna (e.g., Arctic staghorn sculpin, *Gymnocanthus tricuspis* ((Seth *et al.*, 2013)). While recent observations suggest that invertebrate species may be invading deep-sea and benthic habitats in the Southern Ocean, the potential for highly productive pelagic finfish to invade this region appears low due to minimal projected changes in the thermal gradient (McBride *et al.*, 2014). However, the opening of trans-Arctic trade routes through reduced sea ice cover has been discussed as a potential driver of species invasions through ship-mediated transport and natural dispersal, which would likely alter the dynamics and structure of Arctic ecosystems (Ware *et al.*, 2013; Miller and Ruiz, 2014).

3.1.2.4. Summary of regional impacts

“The progressive redistribution of species and the reduction in marine biodiversity in sensitive regions and habitats puts the sustained provision of fisheries productivity and other ecosystem services at risk, which will increase due to warming by 1°C or more by 2100 compared to the present (*high confidence*).”

IPCC WGII AR5, Ocean Systems, Pörtner et al. 2014.

Recent projections suggest that ecosystems at higher latitudes will generally experience increases in primary production, while those at lower latitudes will experience decreases (Barange *et al.*, 2014). Studies continue to support the vulnerability of tropical (Barange *et al.*, 2014) and polar marine ecosystems (Clark *et al.*, 2013) to climate change, with projected negative impacts on the communities that depend upon these resources for food and economic security (Barange *et al.*, 2014). The interdependence between tropical marine

habitats has been highlighted, suggesting cascading effects associated with habitat losses (Saunders *et al.*, 2014), while evidence of community phase shifts arising from climate-related drivers has been found for tropical ecosystems (Inoue *et al.*, 2013; Bell *et al.*, 2013b; Ainsworth and Mumby 2014) and temperate ecosystems (Wernberg *et al.*, 2013; Thomson *et al.*, 2014; Vergés *et al.*, 2014).

3.1.3. How are these impacts expected to affect fisheries' catch potential?

In AR5, species range shifts and a reduction in marine biodiversity were projected to lead to a redistribution of benefits and impacts for coastal communities and sectors, leading to concerns regarding impacts to food and economic security (Pörtner *et al.*, 2014; Portner *et al.*, 2014). Latitudinal trends suggested that fisheries production and the sustained provision of ecosystem services were likely to be most at risk in tropical regions, while fisheries to the north could experience benefits through poleward range shifts (Pörtner *et al.*, 2014). Research published following the report continues to emphasize the particular risks borne by developing nations and communities in tropical and polar regions who depend on coastal resources for food and economic security (Barange *et al.*, 2014).

3.1.3.1. Tropical fisheries

“Overall, there is high confidence that climate change will impact on fisheries production with significant negative impacts particularly for developing countries in tropical areas, while more northerly, developed countries may experience benefits (Section 6.4.3).”

IPCC WGII AR5, Food Security and Food Production Systems, Portner et al. 2014.

Projections continue to suggest that greater instances of declines in fisheries catch potential are likely to occur in tropical regions (Barange *et al.*, 2014). Evidence also supports the hypothesis that there will be ‘winners’ and ‘losers’ under climate change. For example, eastward range shifts in response to climate-related drivers are expected for skipjack tuna by 2050, leading to increased catches for Pacific Island countries to the east of 170°E and decreased catches for those to the west (Bell *et al.*, 2013a). In Bangladesh, prawn postlarvae fishers have been impacted indirectly by increased intrusion of saline water into agricultural land, which has increased fishing pressure from displaced farmers, while climate-related drivers have and are expected to lead to a net loss in revenue, food security, and livelihood sustainability (Ahmed *et al.*, 2013).

“There is *high confidence* that the availability of fish and invertebrate species associated with coral reefs that are important in many tropical coastal fisheries is *very likely* to be reduced.”

IPCC WGII AR5, Food Security and Food Production Systems, Portner et al. 2014.

Projections also suggest that marine taxa in tropical regions are likely to lose critical habitat (e.g. coral reefs, mangroves, and seagrasses) through phase shifts towards other habitats (e.g., macroalgae) (Kroeker 2012, Ainsworth and Mumby 2014), with corresponding declines in fisheries productivity (Bell *et al.*, 2013a). While phase shifts could lead to new or increased fishing opportunities (e.g., reduction in carnivorous macrobenthos may lead to increased shrimp biomass and landings; (Ainsworth and Mumby 2014), it is likely that local communities will need to abandon traditional harvests in lieu of less valuable but more abundant species (Ainsworth and Mumby 2014). Reduced fitness of commercially important species (e.g., coral trout, *Plectropomus leopardus*; (Johansen *et al.*, 2013)) could also have implications for the sustainability of coral reef fisheries. Additionally, projected poleward and eastward shifts of key species caught by major oceanic fisheries in the tropical Pacific Ocean (e.g., skipjack, yellowfin, and bigeye tuna) are expected to occur in association with a large expansion of the western Pacific Warm Pool—with temperatures in the equatorial Pacific projected to exceed 29°C by 2100—and a relocation of productive waters where warm and cold waters converge (Ganachaud *et al.*, 2013; Lehodey *et al.*, 2012; Salinger *et al.*, 2012).

3.1.3.2. Temperate and subtropical fisheries

The link between sea surface temperatures and fisheries landings in the Mediterranean Sea has been explored by multiple studies (Tzanatos *et al.*, 2013; Teixeira *et al.*, 2014; Gamito *et al.*, 2015). Portuguese fisheries have experienced declines in landings of temperate fish and increased landings of subtropical and tropical species between 1970 and 2011, which have been statistically linked to changes in sea surface temperatures (SST); since the latter species are often of greater commercial importance, increased SST under climate change may offer opportunities for fishers in the Mediterranean (Teixeira *et al.*, 2014). Conversely, culturally-important sponge fisheries in the Mediterranean Sea have been threatened by climatic and anthropogenic stressors such as ocean warming, overfishing, and species invasions (Pérez and Vacelet, 2014), all of which are likely to continue under climate change. While it is uncertain whether

small-scale fisheries will have the mobility to follow target species, those with access to multiple gears may be able to adapt more easily to climate-related changes in stock composition (Gamito *et al.*, 2013, 2015; Teixeira *et al.*, 2014).

On the other hand, it is important to note that declines in catch have been projected for fisheries in the Northeast Pacific (77% to 85% reduction in landings; Ainsworth *et al.*, 2011); 13.2% decline in catch potential; Barange *et al.*, 2014), Northwest Atlantic (20% to 22% declines; Guenette *et al.*, 2014), and Northeast Atlantic (8.3% decrease in maximum catch potential; Jones *et al.*, 2014). At the ecosystem level on the Nova Scotian shelf of eastern Canada, synergistic climate change effects were projected to reduce biomass by 19% (optimistic scenario) to 29% (pessimistic scenario), with accompanying declines in fisheries catch potential by 20% to 22%, respectively (Guenette *et al.*, 2014). Declines in seafloor biomass have also been projected for more than 80% of deep-sea biodiversity hotspots around the world (Jones *et al.*, 2013).

Given that low-oxygen waters include areas of upwelling associated with the world’s largest fisheries, expansion of OMZs may pose a concern to food security. For example, while Peruvian anchoveta are not affected by a shallow oxycline, sardines avoid such areas (Bertrand *et al.*, 2010). Habitat compression may also increase the vulnerability of commercial species to fishing and, in turn, potentially increase the risk of overfishing (i.e., increasing catch per unit effort; Stramma *et al.*, 2011). The implications of eOMZ expansion in terms of ocean biogeochemical cycling of carbon, nitrogen, and sulphur are therefore highly uncertain given the multiple feedbacks between physical and biological mechanisms (Keeling *et al.*, 2010; Gilly *et al.*, 2013).

3.1.3.3. Polar fisheries

Polar—and especially Arctic—ecosystems and corresponding fisheries have been experiencing a marine “Klondike” (Christiansen *et al.*, 2013). For example, declines in the temporal and spatial extent of sea ice cover may provide finfish fisheries with greater access to stocks, thereby providing new opportunities (Constable *et al.*, 2014). The Antarctic krill fishery has been suggested as a significant opportunity for expansion under climate change through changes in sea-ice extent, but the opportunities and losses with respect to this fishery remain ambiguous (Constable *et al.*, 2014). For instance, projections have suggested that climate change could have a negative effect on Antarctic krill growth habitat (Hill *et al.*, 2013), with krill embryos and larvae exhibiting enhanced energetic requirements and delayed development in response to elevated CO₂ levels (Kawaguchi *et al.*, 2013).

In contrast, small-scale fishing communities in polar regions are likely to be detrimentally affected climate- and ocean acidification- induced changes in fisheries due to a large reliance on local harvests for food and economic security (AMAP 2013). Despite the projected increases in the relative abundance of fish stocks, increase competition over new resources and reduced availability of traditionally harvested species may severely inhibit fishing opportunities, while limited management procedures provide few precautionary controls to ensure sustainable fisheries management under climate change (AMAP 2013).

3.1.4. What economic impacts are expected for fishing and auxiliary industries?

Healthy marine systems play a critical role in supporting fisheries, which contribute significantly to jobs, food security, and the wealth of nations (e.g., Teh and Sumaila, 2011). As noted in earlier sections, climate change and ocean acidification are already impacting marine systems, and are predicted to continue doing so at an increasing rate. Populations of marine plants and animals might respond in various ways: populations might benefit (e.g., increased reproductive or growth rates), suffer adverse effects (e.g., increased mortality or decreased growth rates), or redistribute to more suitable areas. As stated by Sumaila *et al.* (2011), these responses will alter the availability of fish to fisheries, with economic consequences manifested in corresponding changes in the price and value of catches, fishing costs, fishers' incomes, fishing companies' earnings, discount rates, and economic rents (that is, the surplus after all costs—including 'normal' profits—have been covered).

While it is difficult to predict ecosystem responses to ocean warming and acidification, it is even more difficult to predict the ways in which people will individually or collectively alter their behaviour in anticipation of—or in response to—ecosystem changes. There is a need to improve our understanding on the behaviour responses of human community to ecosystem changes, particularly those who are engaged in ocean related sectors such as fishermen, aquaculture operators. Responses to fisheries impacts are likely to occur at both an individual (or firm) level, and at national, regional, and global levels. Responses might be either proactive or reactive. A proactive fishing company, for instance, might be uncertain about how the stocks it targets will respond to climate change and acidification and, in the face of that uncertainty, might decide on a variety of adaptation strategies (e.g., diversification of capital investment into other fisheries or opportunities; gradual reallocation of its assets to new areas where it expects fishing to

improve (Herrick *et al.*, 2010). In contrast, reactive firms will simply wait for changes to occur before responding. At a national level, a country might act proactively by using capacity-reduction measures to increase the profitability (and thus the resilience) of its industry. A country might also enact similar measures after a change has occurred in order to organize or finance a sustainable transition for fisheries.

3.1.4.1. Economic implications for tropical regions

“Socioeconomic vulnerability is highest in developing tropical countries involving a risk of reduced supplies, income, and employment from marine fisheries (*high confidence*).”

IPCC WGII AR5, Ocean Systems, Pörtner et al. 2014.

The latest IPCC report estimated that the reduction in coral cover and associated fisheries production would likely lead to net revenue losses as early as 2015 in the Caribbean (Wong *et al.*, 2014); 5.4.3.3). In contrast, increased catches in skipjack tuna are projected for the eastern Pacific Islands, which are expected to lead to increases in revenue (Bell *et al.*, 2013b). On the other hand, decreased catches in the exclusive economic zones of Papua New Guinea (-11%) and the Solomon Islands (-5%) translate to a 0.1 to 0.4% decline in GDP due to the large size of their economies (Bell *et al.*, 2013b). In addition, diversity of exploited species is projected to decrease under both the RCP8.5 and 2.6 scenarios due to a decrease in habitat suitability for tropical species, with the magnitude of the decline being positively related to the emission level (Jones and Cheung, 2014). Such projected trends are robust to the use of different modelling approaches (Jones and Cheung, 2014).

3.1.4.2. Economic implications for temperate and subtropical regions

A recent study projected that climate-related changes in relative environmental suitability and fisheries catch potential would translate to a 10% loss in net present value within the UK's exclusive economic zone by 2050, without accounting for the additional fuel and gear costs that might be incurred (Jones *et al.*, 2014). The quality of fish stocks may also be detrimentally affected through increased frequency of disease transfer and cumulative mortality under warmer temperatures; for instance, disease such as *Ichthyophonus* (ichthyophoniasis) reduce the market value of finfishes, thereby having wide-ranging and significant economic and ecological impacts (Burge *et al.*, 2014).

Moreover, the loss of economically valuable corals—such as the red corals (*Corallium rubrum*) in the Mediterranean— could lead to direct losses in revenue of between 200–300 US\$ kg⁻¹ and 50,000 US\$ kg⁻¹ (Bramanti *et al.*, 2013). Commercially harvested sponges could also be detrimentally affected by climate-induced species invasions, which are already occurring within the Mediterranean (Pérez and Vacelet 2014).

Economic impacts are likely to extend to seaports (e.g., increased maintenance costs associated with corrosion from ocean acidification; damage to infrastructure through storm surges, sea level rise, and flooding; disruption of transport) (Becker *et al.*, 2013; Nursey-Bray *et al.*, 2013).

3.1.4.3. Economic implications for polar regions

“The physical, biological, and socioeconomic impacts of climate change in the Arctic have to be seen in the context of often interconnected factors that include not only environmental changes caused by drivers other than climate change, but also demography, culture, and economic development.”

IPCC WGII AR5, Polar Regions, Larsen et al. 2014.

Few existing studies have quantitatively assessed the local economic benefits and risks associated with ocean warming and acidification in polar coastal regions (AMAP 2013). While recent attempts have been made to assess the socio-economic impacts of ocean acidification in polar regions (Hilmi *et al.*, 2013; AMAP, 2013), a limited understanding of how the effects of ocean acidification might transfer between trophic levels largely confines attempts to single-species assessments (Hilmi *et al.*, 2013). From a qualitative perspective, increased marine access through sea-ice loss in the Arctic is likely to lead to increased industrial development, resource extraction and shipping opportunities (Miller and Ruiz, 2014), with the accessibility of near-coastal and remote marine zones of all eight Arctic nations anticipated to increase by up to 28% by 2050 (Post *et al.*, 2013).

Community-based assessments of socioeconomic impacts to rural and Indigenous coastal populations risk undervaluing the importance of marine harvests to Arctic cultures given their role in forming cultural identity and providing essential nutritional requirements (AMAP, 2013). While the broad range of species harvested by Indigenous communities offers opportunities for adaptation through alternative harvests, they may be accompanied by seasonal or cultural losses (AMAP, 2013).

“Increased economic opportunities are expected with increased navigability in the Arctic Ocean and the expansion of some land- and freshwater-based transportation networks.”

IPCC WGII AR5, Polar Regions, Larsen et al. 2014.

While increased anthropogenic activity in the Arctic has been linked to economic opportunities and ecological concerns (Larsen *et al.*, 2014), Whiteman *et al.* (2013) argue that the global economic implications associated with climatic change in the Arctic have been ignored. For instance, the release of methane from thawing permafrost off northern Russia alone has been valued at \$60 trillion in the absence of mitigation (Whiteman *et al.*, 2013). After accounting for global changes in sea level, economic and non-economic sectors, and the melting of ice sheets, the mean projected cost of climate-related impacts fell between \$82 trillion (‘low-emissions’ scenario) and \$400 trillion (‘business-as-usual’ scenario), of which the majority of the projected cost (80%) is expected to be borne by developing nations in Africa, Asia and South America (Whiteman *et al.*, 2013).

As the Arctic is a hotspot of ocean acidification, recent projections suggest that ocean acidification will reduce the expected increase in fisheries potential in the Arctic from climate change. Particularly, a recent study projected that total fisheries revenue in the Arctic region will increase by 39% (14–59%) by 2050 relative to 2000 under the Special Reports on Emission Scenario (SRES) A2 while ocean acidification is expected to reduce the potential increases in catch and economic indicators such as revenues (Lam *et al.* in press).

3.1.5. How are these impacts expected to alter food security?

“Changes in the abundance and distribution of harvested marine species “are expected to continue[,] with negative impacts on nutrition and food security for especially vulnerable people, particularly in some tropical developing countries {7.3.3.2}, but with benefits in other regions that become more favourable for aquatic food production (*medium confidence*). {7.5.1.1.2}”

IPCC WGII AR5, Food Security and Food Production Systems, Portner et al. 2014.

As reported in AR5, the future consequences of ocean warming and acidification on food security derived from aquaculture and capture fisheries are difficult to estimate (Portner *et al.*, 2014). However, regional trends highlighted in AR5

illustrate the particular vulnerability of developing nations and the rural and indigenous communities that depend on tropical and polar marine ecosystems for food security (Larsen *et al.*, 2014; Portner *et al.*, 2014; Pörtner *et al.*, 2014).

Declines in fisheries catch potential are expected to detrimentally impact food security in tropical nations, with impacts predominantly affecting those in South and Southeast Asia and small-island developing states (SIDS) (Barange *et al.*, 2014). For instance, a 20% reduction in coral reef fish production by 2050 is expected to detrimentally affect food security for Pacific Islanders, with even well-managed fisheries failing to meet nutritional requirements of a growing population (Bell *et al.*, 2013a). While acidification and warming-related declines in fisheries productivity in South and Southeast Asia are expected to reduce food security, opportunities have been identified through the regions' growing aquaculture production (Barange *et al.*, 2014). Although range shifts have been projected to increase the availability of fish stocks in polar regions, these projections are uncertain (28.3.4.1, Larsen *et al.*, 2014; AMAP 2013). The impacts of ocean acidification and increased competition through increased accessibility arising from reduced ice cover (Miller and Ruiz 2014; Constable *et al.*, 2014; Lam *et al.*, 2014) could offset these benefits.

“... food security for many Indigenous and rural residents in the Arctic is being impacted by climate change, and in combination with globalization and resource development food insecurity is projected increase in the future.”

IPCC WGII AR5, Polar Regions, Larsen et al. 2014.

Indigenous fishing communities that depend on traditional marine resources for food security are particularly vulnerable to climate change through a reduced capacity to conduct traditional harvests due to limited access to—or availability of—resources (Larsen *et al.*, 2014); 28.2.5). For instance, shellfish and traditional clam beds—which form an integral part of the culture, economy and diet of many Indigenous communities situated along the Pacific Coast of North America—may be affected by increased sea surface temperatures, sea level rise, and changes in ocean chemistry and circulation patterns (Lynn *et al.*, 2013). This has critical implications for the food and economic security of coastal Indigenous communities, the preservation and transfer of their traditional knowledge, and the legal upholding of their rights to access traditional resources (Lynn *et al.*, 2013).

3.1.6. What ramifications may arise with respect to multilateral business agreements (e.g., fishing in EEZs) and international agreements? What geopolitical impacts are likely to occur?

The IPCC report noted that changes in the accessibility of marine resources and the magnitude of operation costs would likely lead to geopolitical challenges for managing trans-boundary stocks and mitigating overexploitation (Pörtner *et al.*, 2014). Although few to no quantitative assessments of the impacts of such changes (e.g. on the economics of bi- and multilateral partnerships) have been conducted, some possible trends can be highlighted.

For example, the geopolitical consequences associated with the increasingly ice-free Arctic are of critical concern not only with respect to maintaining the ecological structure and function of polar ecosystems, but also to the local communities that depend upon marine resources for a range of ecosystem services (Christiansen *et al.*, 2013). Likewise, the need to shift fishing pressure toward pelagic stocks—primarily tuna—in the Pacific Islands in response to projected declines in coral reef fish stocks used for subsistence highlights the importance of strengthening trans-boundary fishing agreements and implementing effective governance (Bell *et al.*, 2013a). In West Africa, where fisheries production is expected to increase under climate change, improved fisheries governance would be necessary to ensure that distant-water fleets do not detrimentally affect local opportunities (Barange *et al.*, 2014).

Policy-related barriers that may arise for industrial stakeholders include: restricted access to international markets due to trade agreements; harvest closures at inopportune times for fishers (e.g., seasons coinciding with higher prices); and conservation measures or regulations that limit industrial expansion (Fleming *et al.*, 2014a). In fact, these issues can be relevant even within country EEZs as demonstrated for Mexico by Sumaila *et al.* (2014).

Miller *et al.* (2013a) illustrate that the likelihood of abrupt and unpredictable changes in the productive potential and migratory behaviour of exploited fish stocks may disrupt current management arrangements, with particular relevance to the cooperative management of shared fish stocks. The authors discuss the value of contingency planning based on anticipation of the possibility of such events and, after reviewing a number of case studies, identify three ways to achieve effective and proactive governance of internationally shared fisheries in the face of climate change: (1) creative mechanisms to improve the economic viability of

cooperation between agents sharing a common fished stock; (2) mechanisms to improve the resilience and adaptability of cooperative management arrangements to environmental perturbations; and (3) improved integration of scientific research and ecosystem monitoring in the management of shared fisheries (Miller *et al.*, 2013a).

3.1.7. What new evidence supports the theory of an emerging ‘winners and losers’ gap?

New evidence published after AR5 further strengthens the conclusion that there is an emerging ‘winners and losers’ gap associated with climate change impacts, with particular relevance for developing nations. For instance, in a recent global assessment of 67 marine exclusive economic zones, Barange *et al.* (2014) projected that fisheries production would likely increase in West Africa and decrease in South and Southeast Asia by 2050, both of which represent regions that are highly dependent upon fisheries for food and economic security. Range shifts have also been implicated in a redistribution of benefits and losses under climate change (e.g., eastward shifts of tuna stocks are likely to benefit some Pacific Island nations, while leading to losses for others; Bell *et al.*, 2013a). Whiteman *et al.* (2013) noted that developing nations would likely bear 80% of the total cost—estimated at US\$82 to US\$400 trillion—associated with climate-related impacts arising from the release of methane gas in the Arctic.

Ecologically, ‘winners’ and ‘losers’ are also projected through community phase shifts and trophic cascades (Inoue *et al.*, 2013; Bell *et al.*, 2013b; Ainsworth and Mumby 2014; Vergés *et al.*, 2014), with some species outcompeting others under multiple stressors (Brown and Thatje, 2014).

3.2. Aquaculture

3.2.1. How is climate change expected to impact future shellfish and fish aquaculture?

Climate and acidification-related impacts to aquaculture are expected to vary by location, species, and method of aquaculture. Latitudinal and taxon-specific trends have been identified, with the farming of higher trophic level species (e.g., trout farming in northern Mediterranean countries) expected to exhibit higher mortality rates and lower productivity under warming (Rosa *et al.*, 2014). Conversely, inland production in southern countries tends to be based on more resilient species (e.g., carp and tilapia farming in Egypt), and may therefore experience increased metabolic rates, growth rates, and overall production (Rosa *et al.*, 2014). In the Pacific Islands, coastal

aquaculture is projected to experience reductions in production efficiency, while freshwater aquaculture (e.g., Nile tilapia, *Oreochromis niloticus*) is projected to experience greater farming potential through faster growth rates associated with warming and an increase in the availability of freshwater through greater precipitation, thereby offering opportunities to contribute to food security (Bell *et al.*, 2013a).

Sea level rise is further expected to exacerbate aquaculture production through increased intrusion of saline water into deltas and estuaries, where aquaculture commonly occurs (e.g., Mekong and Red River deltas in Viet Nam and the Ganges-Brahmaputra Delta in Bangladesh; De Silva, 2012), but may be countered by farming more saline-tolerant and brackish-water species (Rosa *et al.*, 2014; Swaminathan, 2012). In Bangladesh, where fish cultivation and agriculture are the main occupations in coastal regions, fish cultivators have already reported production problems associated with increased salinity and disease prevalence (Garai, 2014).

The increased threat of infectious disease to aquaculture under climate change has been explored recently, with shellfish larval dispersal having been implicated in the transport of disease (Rowley *et al.*, 2014). The susceptibility of molluscs and crabs to disease (e.g., vibriosis) has been linked to sea surface temperatures, and temperate-driven range shifts may lead to an influx of new diseases (Rowley *et al.*, 2014). With respect to regional variations, a global study found that cumulative mortality from disease was relatively higher in tropical aquaculture than in temperate aquaculture (88% versus 34%, respectively), with juvenile invertebrates exhibiting greater vulnerability in comparison with adult finfish (Leung and Bates, 2013). Importantly, the toxicity of common pollutants to fish increases at higher temperatures, while a decrease in salinity has been shown to increase toxicity for some species by altering the chemical speciation of metals; however, the latter relationship is complex since higher salinities can bind metals to particles and thereby facilitate contaminant intake (Fabbri *et al.*, 2014). Studies have also warned that increased ocean temperatures and eutrophication under climate change may lead to a greater occurrence of toxic tides (e.g., HABs in the Mediterranean Sea), and thereby detrimentally affect aquaculture production and human health (Rosa *et al.*, 2014; Himes-Cornell *et al.*, 2013). Pathogen range expansions induced by climate change may increasingly affect temperate regions as species and pathogens shift polewards, and in turn may pose a threat to human health through the consumption of contaminated seafood and water-borne

pathogens (Rosa *et al.*, 2014). This highlights a management concern for developing nations at lower latitudes that would otherwise benefit from increased food security through aquaculture.

3.2.2. What are the projected consequences of changes in aquaculture production on global food and economic security?

Aquaculture production formed 90.4 million tonnes (live weight equivalent) as of 2012, contributing approximately US\$144.4 billion to the global economy in food products and an additional US\$222.4 million in non-food products, such as pearls and seashells (FAO 2014). While few studies since 2013 have provided quantitative estimates of economic impacts through changes in aquaculture production under climate change, studies have assessed the likelihood of regional losses or gains.

Despite the capacity to control for conditions, aquaculture is likely to be both negatively and positively affected by changes in precipitation, temperature, drought, storms, and floods, all of which would have socioeconomic implications (Li *et al.*, 2014). For instance, aquaculture facilities in the Caribbean and Latin American regions are likely to be vulnerable to ocean acidification and extreme weather events, with the potential for flooding in the Caribbean to affect local facilities (FAO 2014). Similarly, the economically valuable black pearl industry in Polynesia is expected to be vulnerable to increased sea surface temperature and ocean acidification, which—given its role in employing thousands of people on remote atolls—is expected to lead to a loss in local revenue and employment (Bell *et al.*, 2013a). Yet another example is that of the valuable catfish farming industry in the Mekong Delta, Viet Nam, which supports 150,000 livelihoods and produces 1 million tonnes of fish annually, and which is expected to be detrimentally affected by saline intrusion accompanying sea level rise (Swaminathan 2012). As the greatest producers of aquaculture, small-scale Asian practices in coastal bays are at high risk from storms, wave surges, and high winds, with the potential for significant losses for local livelihoods (De Silva 2013). Li *et al.* (2014) estimated both positive and negative economic impacts for Chinese aquaculture, with local latitudes likely to experience predominantly negative impacts due to increased water temperatures and reduced primary production, leading to significant impacts to food security and employment. In particular, increased precipitation yielded significant benefits to profit, while increased weather variability was associated with lower profit, highlighting the sensitivity of aquaculture production to sudden, extreme weather events (Li *et al.*, 2014).

With decreased dependence on wild-caught stocks for fishmeal and farming combined with technological developments, aquaculture could significantly contribute to global food security under climate change (Barange *et al.*, 2014). Longer growing seasons, faster growth rates, and lower winter mortality arising from increased temperatures could yield positive effects at mid- to high-latitudes (e.g., extended breeding periods for Indian carps in fish farm hatcheries in West Bengal) (Li *et al.*, 2014, De Silva 2013). However, trade-offs are expected to arise as aquaculture industries compete with other sectors (e.g., wild-caught fisheries, coastal tourism) for different ecosystem services derived from coastal and wetland habitats that are sensitive to climate change (Ruckelshaus *et al.*, 2013).

3.3. Coastal tourism

The rationale for asking about the consequences of ocean warming and acidification on coastal tourism is two-fold. Firstly, tourism is one of the largest sectors in the global economy, and coastal tourism represents a significant part of tourism business around the world. Therefore, climate-induced impacts to tourism have considerable ramifications for local, national and regional economies (employment, transportation, agriculture, etc.). Secondly, coastal tourism is strongly dependent on climate and underwater conditions, as well as on landscapes. This sector is thus very sensitive to both gradual changes in climatic and oceanic conditions, and to extreme and abrupt events.

When combined, ocean warming and acidification will lead to changes in sea surface temperature, sea life and sea level rise (Church *et al.*, 2014; Hoegh-Guldberg *et al.*, 2014; Pörtner *et al.*, 2014; Howes *et al.*, 2015). In addition, climatic events such as storms and cyclones (that both induce marine surges, notably) have to be considered. Together, these drivers will lead to changes in the basic conditions for coastal tourism, i.e. climatic parameters (air temperature, precipitations, wind speed, etc.), underwater parameters (sea surface temperature, invasive species such as jellyfishes, etc.), and coastal hazards (erosion, marine flooding, etc.). Such changes will affect the main components of the tourism industry (i.e. tourists' preferences, tourism operators' strategies and the transportation market) and thus the tourism supply and demand balance at the global scale. However, it is very complex to forecast changes in tourists' preferences, companies' adaptation strategies, and transportation companies' responses to changes in a destination's attractiveness. Models have however begun to emerge in the past decade,

and although they face large limitations (Arent *et al.*, 2014), have started identifying key questions related to tourism flows (3.3.1), tourism operators' adaptation strategies (3.3.2), and economic impacts at the local scale (3.3.3).

3.3.1. What are the consequences of ocean warming and acidification impacts on tourism flows?

“Developing countries and small islands within the tropics dependent on coastal tourism will be impacted directly not only by future sea level rise and associated extremes but also by coral bleaching and ocean acidification and associated reductions in tourist arrivals (*high confidence*). {5.4.3.4}”

IPCC WGII AR5, Coastal Systems and Low-Lying Areas, Wong et al. 2014.

As described in AR5, changes in the quality and abundance of coral reef cover are expected to cause socio-economic and environmental concerns for small island developing nations and developing countries, with particular relevance to the tropics (Wong *et al.*, 2014).

However, tropical coastal areas will not be the only ones impacted. In Europe for example, coastal Spain is expected to experience impacts to coastal tourism through water shortages, reduced opportunities for different tourism modalities, and, in turn, reduced job opportunities in the tourism industry (Ciscar *et al.*, 2011; Saurí *et al.*, 2014). In particular, findings suggest that there may be ‘winners’ and ‘losers’ in coastal tourism as well, since higher temperatures could discourage southward flows of tourism in Europe while reinforcing northwards flows (Magnan *et al.*, 2012, DiSegni and Shechter 2014).

Species range shifts are also expected to alter tourism flows. In the United States, for example, range shifts could yield new opportunities for recreational fishing in temperate regions, while warmer conditions could benefit some species purposively introduced for recreational fishing (Nelson *et al.*, 2013). Conversely, increases in the prevalence of tropical box jellyfish through climate-induced poleward range shifts could impact coastal tourism and water-related activities in subtropical and temperate regions. In particular, a recent study found that Irukandjii jellyfish (*Alatina nr mordens*) polyps were resilient to the combined effects of ocean acidification and warming, suggesting that these polyps would be able to colonize new areas under climate change and thereby increase socioeconomic losses and hospitalization events (Klein *et al.*, 2013). Increased prevalence and transmission of diseases are also

expected under warmer ocean temperatures, with existing empirical evidence of poleward shifts in disease outbreaks under warmer conditions (see Section 3.4.1; Burge *et al.*, 2014). Importantly, adverse publicity accompanying an increased risk of disease transmission in tropical and subtropical regions could have deleterious impacts on coastal tourism (DiSegni and Shechter 2014).

3.3.2. What are the consequences of ocean warming and acidification impacts on tourism operators' strategies?

Tourism operators—whether they are an international company or a small resort owner—will experience changes in their business conditions, especially due to warming (air and ocean) and sea level rise. It is currently unclear to what extent ocean acidification will have direct impacts on destinations' attractiveness (e.g., on underwater landscapes in areas depending on scuba diving, or on natural/cultural patrimony in some French Atlantic hotspots for oyster and mussels farming), as no scientifically sound paper has been identified in this study.

Key impacts arising from warming and sea level rise will include the degradation of coastal infrastructures such as resorts and roads (through coastal erosion, marine flooding, high winds, rivers' inundation), on the one hand, and changes in destinations' attractiveness due to modifications in air and sea temperatures, landscapes, bathing conditions, etc. on the other hand. Coastal flooding, for example, is increasingly a concern both for developed and developing cities, with coastal populations expected to grow by 25% by 2050 (Aerts *et al.*, 2014). In an innovative study, McNamara and Keeler (2013) employed a barrier-island model coupled with an agent-based model to assess climate-related impacts to coastal real estate along regions of the US East Coast, and found that informed property owners would invest in defensive expenditures before abandoning coastal real estate at some critical risk threshold, signifying a period of significant price volatility. They further found that the rate of sea level rise (SLR) was a major determinant of real-estate market outcomes, with higher rates of SLR corresponding with declining property values and faster abandonment (McNamara and Keeler 2013).

Climate change impacts to marine ecosystem can also impact tourism. Rising ocean temperatures have already caused widespread coral bleaching and this is expected to get worse. The mass bleaching in Southeast Asia in 2010 profoundly reduced tourism revenue. Doshi *et al.* (2012) estimated the cost of this event to be \$50–80 million in Thailand, Indonesia, and Malaysia alone. Bleaching events

in Tanzania and nearby Indian Ocean reefs were shown to reduce non-market benefits derived from coral reefs (Andersson 2007; Ngazy *et al.*, 2004). An analysis of vulnerability of the Australia's tourism revenue from the Great Barrier Reef suggests that coral reef losses due to warming and acidification places up to \$2B in annual tourism revenue at risk (Hoegh-Guldberg and Hoegh-Guldberg 2008)

Regarding destinations' attractiveness, it is important to mention that some destinations will likely experience a decrease in attractiveness, while others will benefit from changing conditions (Ciscar *et al.*, 2011; Magnan *et al.*, 2012; Arent *et al.*, 2014). This indicates that various strategies must be evaluated when considering the diversity of tourist operators' responses, which are influenced by their level of dependence on local environmental conditions. Schematically, while it will be possible for international companies to relocate their investments, small business owners will face limitations when endeavouring to protect local resort infrastructure.

3.3.3. What are the economic consequences to be expected from ocean warming and acidification?

These examples illustrate that ocean warming and acidification will not only affect tourism in small islands and developing countries, but also in developed areas such as Europe and the United States. Consequently, the economic implications of coastal tourism are expected to be significant in most of the destinations around the world, and especially at the local scale (i.e., many tourism-dependant coastal economies). In the United States, for example, 7.52 million jobs and \$1.11 trillion in sales are supported by tourism, with the majority of tourism occurring in coastal regions that are expected to experience changes in weather conditions and extreme events, such as typhoons and hurricanes (Himes-Cornell *et al.*, 2013). Beach recreation values are also expected to decline in response to narrower beaches resulting from SLR and erosion, with considerable impacts to local economies (e.g., \$1 billion loss between 2006 and 2080 in North Carolina (Whitehead *et al.*, 2009; Nelson *et al.*, 2013). As principal assets of coastal tourism, the loss of beaches could significantly impact local economies in subtropical and tropical regions, and could incur additional costs associated with coastal defence protection and infrastructure repairs (DiSegni and Shechter, 2014).

Similarly, the loss of ecosystem services associated with SLR-induced coastal erosion in Europe is estimated at €2.9 billion per year by 2050, resulting in an almost 15% decrease in coastal ecosystem service values compared to 1975 (Roebeling *et al.*, 2013).

In South America, the coastal lagoon ecosystems in Uruguay provide a range of ecosystem services, including food, fuel and fibre, flood and storm protection, erosion control, and carbon sequestration (Fanning, 2014). In particular, climate-induced impacts to ecosystem service values in a coastal lagoon, Laguna de Rocha, were calculated for carbon sequestration services (annual revenue of €178,487 to €290,540 between 2008 and 2011 in the Laguna de Rocha) and habitat maintenance and cultural values (damage costs avoided method yielded an inferred value of US \$300,000 between 1986 and 2012) (Fanning 2014).

3.4. Human health and wellbeing

3.4.1. What are the possible impacts of climate-related drivers (e.g., diminished food and water security; extreme weather events; increased prevalence and transmission of disease) on human health?

Knowledge regarding the impacts of climate change on human health in coastal regions has departed little from that outlined in AR5 (5.4.3.5, Wong *et al.*, 2014; 6.4.2.3, Pörtner *et al.*, 2014).

“Impacts on the health and well-being of Arctic residents from climate change are significant and projected to increase—especially for many Indigenous peoples (*high confidence*).”

IPCC WGII AR5, Polar Regions, Larsen et al. 2014.

Hosts and parasites are likely to accompany species poleward range shifts under climate change, with disease outbreaks already having been witnessed under warmer conditions (e.g., faster replication of disease among corals in the Caribbean) (Altizer *et al.*, 2013). Such diseases can lead to community shifts and trophic cascades through the loss of habitat or keystone species (Altizer *et al.*, 2013). For instance, Arctic warming has been projected to facilitate disease transmission between eastern and western Arctic species (Post *et al.*, 2013). While these impacts predominantly focus on ecological systems, such changes are likely to affect human health through declines in food security (e.g., disease propagation in crops or traditional foods) and increased opportunities for pathogen transfer between hosts (Altizer *et al.*, 2013).

Human exposure to diseases may also increase under climate change through storm surges and sea level rise, each leading to an expansion of the geographical and seasonal ranges of bacteria (Burge *et al.*, 2014). For instance, a poleward range shift of outbreaks of *Vibrio* has been witnessed as far north as the Baltic Sea and Alaska

(Burge *et al.*, 2014). As one of the most prevalent food-borne diseases in Europe, *salmonellosis* is likely to be exacerbated by climate change as its frequency of occurrence is directly affected by temperature (i.e., 5-10% increase in the number of cases for each °C increase above a threshold of 5°C (Kovats *et al.*, 2004). Sub-Saharan Africa is projected to experience a southern climate-induced shift in malaria incidences, while additional health concerns include food insecurity, hunger and malnutrition, natural disasters, air pollution, communicable diseases (e.g., HIV/AIDS), non-communicable disease, high injury burden, mental health, and occupational health (e.g., heat stress) (Ziervogel *et al.*, 2014). Similarly, SIDS have been framed as ‘canaries in the coal mine’ with respect to climate change and health given their dependence on marine resources for nutrition and the prevalence of infectious diseases, each of which are expected to be affected detrimentally by climate change (Hanna and McIver 2014).

Climate change is also expected to indirectly impact human health through sea level rise which will increase the risk of the flooding of agricultural land in coastal regions, with potential losses in food security (Wheeler and Braun 2013), while declines in or redistributions of fisheries catch potential could also reduce access to nutrition (Barange *et al.*, 2014) (e.g., observed shifts in anchovy and sardine regimes in the Pacific Ocean; Wheeler and Braun 2013). Harmful algal blooms (HABs) and toxins associated with climate change have continued to be identified as priority areas for research (Fleming *et al.*, 2014a). HABs are expected to increase in frequency through higher coastal eutrophication, and are likely to have detrimental effects on coastal productivity, nursery grounds, biodiversity, and human health through the consumption of contaminated seafood (Himes-Cornell *et al.*, 2013; Marques *et al.*, 2014).

Despite these concerns, data supporting causal pathways between climatic variables and human health outcomes through marine ecosystems are still limited (Ziervogel *et al.*, 2014).

3.5. Brief insights on coastal adaptation across sectors

The previous sector-based sections focus on the impacts expected from ocean acidification and warming. They do not consider the potential for adaptation, which aims precisely to limit the impacts of changes in environmental conditions. For instance, while international fisheries companies or international tourism operators can develop their activities elsewhere, local to national stakeholders (enterprises, decision-makers,

populations) must identify place-based solutions. This induces a wide range of possible strategies, but unfortunately very few concrete ones have been studied to date. Examples of adaptation strategies to climate change effects on fisheries include changing target species (e.g., Cheung *et al.*, 2013) and multi-lateral fisheries agreement (e.g., Miller *et al.*, 2014). Published experiences are scarce, preventing us from drawing generic conclusions regarding adaptation strategies and their cost-effectiveness. However, despite this limitation, this section provides some reflections from recent literature on key topics for coastal adaptation.

3.5.1. What evidence exists of the capacity for coastal communities and sectors to mitigate and adapt to climate change?

3.5.1.1. Adaptation in fisheries and auxiliary sectors

The capacity for fisheries to mitigate and adapt to climate change has been increasingly studied in different regional contexts. For instance, three fleet dynamic models were used to investigate the effects of climate change on the ecological, economic, and social viability of the Tasmanian rock lobster fishery in southern Australia, highlighting the importance of dynamic adaptation in response to environmental conditions and stock abundance (Hamon *et al.*, 2014). In particular, latitudinal trends were found in which stock size increased polewards through higher growth rates accompanying increased temperatures, with a corresponding redistribution of fishing effort polewards; however, recruitment is expected to eventually decline under climate change and thereby potentially counteract projected benefits (Hamon *et al.*, 2014).

“Key adaptations for fisheries and aquaculture include policy and management to maintain ecosystems in a state that is resilient to change, enabling occupational flexibility, and development of early warning systems for extreme events (*medium confidence*).”

IPCC WGII AR5, Ocean Systems, Pörtner et al. 2014.

Livelihood diversification continues to be supported within the literature as a viable adaptation strategy in response to reduced production in some fisheries and aquaculture operations (Bell *et al.*, 2013a; Ruckelshaus *et al.*, 2013). For instance, poleward range shifts may provide opportunities for fisheries to redirect fishing effort towards emerging fisheries; however, the capacity for fisheries to capitalize on these shifts would depend on the

adaptive capacity of local economic, cultural, and regulatory institutions (Ruckelshaus *et al.*, 2013; Nelson *et al.*, 2013).

Adaptation options for aquaculture production have been suggested. Livelihoods based on pearl production, for example, may be supported through deeper-water cultivation, selective breeding, and selection of suitable sites for production (Bell *et al.*, 2013a). Indeed, Richards *et al.* (2015) concluded that aquaculture is likely to be more viable in the future than wild fisheries due to the capacity to monitor and modify conditions to avoid excessive stressors arising from ocean acidification and other climate-related drivers. After accounting for different life stages, they further gauged that prawns would likely be more resilient to ocean acidification than scallops in Queensland, Australia, due to a greater diversity of species across a larger geographical distribution (Richards *et al.*, 2015). The capacity for aquaculture stocks to be more resilient to climate change than wild stocks is further suggested due to selective breeding and vaccination, which provide means of increasing stock resilience and reducing the frequency of disease transmission (Himes-Cornell *et al.*, 2013). Intertidal oyster reefs have also demonstrated resilience by exhibiting the capacity to outpace sea-level rise, and can function as buffers to help preserve vegetated estuarine ecosystems and coastal structures from erosion (Rodriguez *et al.*, 2014).

Recent studies exploring climate-related impacts to seafood supply chains have found that despite a comprehensive understanding of impacts at the harvest stage, there is a limited understanding of how these impacts will affect other parts of the supply chain (Fleming *et al.*, 2014b). Increased stakeholder awareness in the Australian seafood industry regarding potential impacts of climate change on supply chains has led participants to highlight constructive adaptation options within their respective sectors, including improved fuel efficiency, breeding programs, altered industry structure, simplified regulations, and improved public awareness (Fleming *et al.*, 2014b).

3.5.2. Adaptation in tourism and coastal sectors

Other coastal sectors will also have to adapt, and some of them already demonstrate some experience in adapting to changing conditions, notably environmental ones. For example, the tourism industry has exhibited high adaptive capacity in response to historical shocks (e.g., financial crises, natural disasters, and disease), strongly suggesting the capacity to respond to future climate-induced variability through dynamic adaptation (Scott 2014). Tourists and recreational fishers in the

Arctic, for example, appear to be flexible to targeting alternative species, suggesting a future change in the relative composition of recreational catches under climate change (AMAP 2013). However, the capacity for stakeholders to respond to long-term changes (e.g., increased mean seasonal temperatures, beach erosion, etc.) is more uncertain. For example, a study evaluating perceptions of climate-related impacts along the Balearic coasts of Spain noted that a lack of concern indicated by citizens could lead to a higher degree of vulnerability since adaptive measures could be seen as unnecessary, despite potential impacts to the region (March *et al.*, 2013). This could, in turn, affect the feasibility of coastal tourism markets given increased vulnerability of local real estate. Forecasting stakeholders' responses to ocean warming and acidification is all the more an uncertain exercise that, as seen in section 3.3, various types of stakeholders are not equal in terms of their interests and adaptive capacities, and thus they will necessarily adopt diversified strategies. Here again, there will inevitably be winners and losers (Arent *et al.*, 2014), both among international tourism companies and small enterprises.

3.5.3. Ecosystem-based coastal adaptation

Adaptation and mitigation strategies suggested in AR5 included the restoration or ecosystem engineering of marine vegetative habitats to assist with buffering climate-related impacts and to provide shelter for fish nurseries and important coastal habitats (Wong *et al.*, 2014). Studies have continued to suggest the capacity for coastal ecosystems, including intertidal wetlands and reefs, to protect coastlines by reducing wave energy, minimizing impacts from storm surges, increasing sedimentation, and/or reducing erosion (Spalding *et al.*, 2014).

“The analysis and implementation of coastal adaptation toward climate-resilient and sustainable coasts has progressed more significantly in developed countries than in developing countries (*high confidence*).”

IPCC WGII AR5, Coastal Systems and Low-Lying Areas, Wong et al. 2014.

The restoration and maintenance of coastal habitats is economically feasible, offering a cost-effective measure of increasing coastal protection and ecosystem services in contrast with “hard” engineering solutions (e.g., seawalls) (Nelson *et al.*, 2013). Moreover, these habitats can yield profit for commercial and recreational activities occurring on the coast, with the potential for the benefit-to-cost ratio of such eco-engineering solutions to exceed that of “hard” solutions (Nelson *et al.*, 2013).

However, while examples of coastal habitat recovery exist (e.g., recovery of cordgrass in New England following die-off), the capacity for habitats to fully recover to their previous state is less certain and subsequent trophic cascades can further reduce habitat resilience (e.g., loss of ribbed mussel beds in New England without cordgrass habitats, which in turn limits cordgrass production) (Brisson *et al.*, 2014). Yet, it is possible that full ecosystem services may be restored without fully recovering the original ecosystem structure (Brisson *et al.*, 2014).

Specific **adaptation scenarios** outlining practical examples of responses to both ocean warming and acidification are required to support effective integration of mitigation and adaptation practices (Shoo *et al.*, 2014). In South East Queensland, Australia, recommendations for conserving tidal wetlands (e.g., salt marshes, mangroves) have been proposed in order to preserve coastal biodiversity and critical ecosystem services (e.g., carbon sequestration; commercial and recreational fisheries; nutrient cycling; recreational activities; etc.) (Shoo *et al.*, 2014). Proposed mechanisms for protecting these ecosystems include strategic zoning that anticipates habitat migration and minimizes climate-related impacts (e.g., Wetland Buffer Guidelines implemented by the Queensland government) and the use of predictive models to situate reserves (e.g., landscape and SLR models) (Shoo *et al.*, 2014).

Ecosystem-based coastal adaptation and mitigation approaches are still emerging, and require an improved understanding of key ecosystem services and values for coastal communities in order to assess risk, aid coastal development planning, and build decision support systems (e.g., Spalding *et al.*, 2014). Managing realignment of coastal ecosystems as they migrate landwards or polewards can aid in proactively planning for future conditions, while hybrid engineering structures can provide an integrated way of conserving ecosystems and ecosystem services (e.g., carbon storage and sequestration; regulating nutrient fluxes; maintaining species biodiversity) while increasing coastal protection (Spalding *et al.*, 2014; Duarte *et al.*, 2013). Expansion of the current REDD+ (Reducing Emissions from Deforestation and Forest Degradation) scheme to include vegetative coastal ecosystems could provide opportunities for small island states to mitigate climate change and could promote restoration of coastal habitats that have been degraded or removed for development (Duarte *et al.*, 2013).

3.5.4. Adaptation in Indigenous, traditional, and small island communities

“Although Arctic residents have a history of adapting to change, the complex interlinkages among societal, economic, and political factors and climatic stresses represent unprecedented challenges for northern communities, particularly if the rate of change will be faster than the social systems can adapt (*high confidence*).”

IPCC WGII AR5, Polar Regions, Larsen et al. 2014.

“The ability of small islands to undertake adaptation and mitigation programs, and their effectiveness, can be substantially strengthened through appropriate assistance from the international community (*medium confidence*). . . Opportunities for effective adaptation can be found by, for example, empowering communities and optimizing the benefits of local practices that have proven to be efficacious through time, and working synergistically to progress development agendas.”

IPCC WGII AR5, Small Islands, Nurse et al. 2014.

While coastal **Indigenous and traditional communities** are particularly vulnerable to climate change through their dependence on traditionally harvested species and local resources, they are also well placed to respond to climate-induced transformation through traditional knowledge accumulated over millennia in response to environmental change (Lynn *et al.*, 2013). A systematic review of the current state of climate-related adaptation in the Arctic revealed that the number of reported adaptation initiatives have increased since 2003, with the majority of initiatives focusing on hunting and subsistence (76 of 157), largely in an Indigenous context (Ford *et al.*, 2014). Frequently, these response included changes in infrastructure (e.g., sites of roads or buildings) or altered locations and times of harvests, and most adaptations were led by individuals, families, or community residents (58%) and occurred at the individual/household scale (52%) (Ford *et al.*, 2014). In coastal British Columbia, Canada, the Gitga’at Nation has demonstrated how enhanced involvement of local citizens in adaptation planning can provide access to expert traditional knowledge that is specific to a given region, thereby providing contextually-informed strategies (Reid *et al.*, 2014). The inclusion of a values and vulnerability assessment combined with the collaborative development of an adaptation plan and capacity building (i.e., skills training), yielded a strong, structured foundation for implementing and monitoring adaptation strategies (Reid *et al.*, 2014). Moreover, the merging of community observations with scientific data

provided validation towards the value of community-based knowledge in contributing to adaptation planning (Reid *et al.*, 2014).

4. DISCUSSION

4.1. Key new areas of development

Research published following AR5 endeavoured to address many of the key uncertainties highlighted by the IPCC. In particular, ecological advances included studies assessing climate-related impacts to different developmental stages of various taxa, as well as an improved understanding of impacts arising from ocean acidification. Studies have recently begun to investigate ecosystem-level responses to climatic stressors, and have identified additional evidence of changes in community size structure and food web composition, with observed examples of community phase shifts across polar, temperate and tropical marine ecosystems. Predator-prey dynamics are also projected to change under ocean acidification and other drivers. Empirical and theoretical evidence continues to support the role of climate velocity in influencing species range shifts.

Areas of development have included studies exploring the capacity for species to genetically and phenotypically adapt to climatic change; however, evidence is still largely obtained from shorter time frames and singular climatic events. While assessments of impacts to food and economic security still primarily comprise qualitative scenario-based approaches, studies have begun to explore methods of obtaining quantitative estimates to inform adaptation and mitigation policies. Attention has increasingly turned towards identifying examples of successful adaptation, with a strong focus on ecosystem services and ecosystem-based adaptation. Coastal sectors aside from fisheries have been mentioned more frequently: for instance, the prospect of obtaining food security through sustainable aquaculture has been explored (Barange *et al.*, 2014; Ruckelshaus *et al.*, 2014), while the capacity for coastal tourism to adapt to changes in climatic conditions has been discussed in different regional contexts (e.g., United States, Mediterranean, Europe).

4.2. Agreement and points of departure from AR5

There continues to be strong evidence that climate change will lead to a redistribution

of benefits and losses at multiple scales, and across human and ecological systems (Barange *et al.*, 2014). For instance, tourism flows, diseases, and species are projected to shift polewards under warmer temperatures (Magnan *et al.*, 2012; DiSegni and Shechter, 2014; Burge *et al.*, 2014; Cheung *et al.*, 2013a, 2013b). Latitudinal trends suggest benefits accruing in polar regions for commercial sectors (e.g., new fishing and extraction opportunities, increased shipping access) (Miller and Ruiz, 2014; Post *et al.*, 2013), while losses are projected for tropical and subtropical regions through reductions in fisheries catch potential and reduced food and economic security (Barange *et al.*, 2014). Ecologically, ‘winners’ and ‘losers’ are also expected to arise from community phase shifts and trophic cascades (Inoue *et al.*, 2013; Bell *et al.*, 2013b; Ainsworth and Mumby 2014; Vergés *et al.*, 2014), with some species outcompeting others under multiple stressors (Brown and Thatje 2014). [Sections 3.1.1.1, 3.1.2, 3.1.3]

Empirical and theoretical evidence continues to support the occurrence of climate-induced range shifts of species and coastal marine ecosystems, which were reported with very high confidence in AR5 (Pörtner *et al.*, 2014). Shallow tropical water systems and coastal mangroves are expected to shift polewards, with species richness increasing at higher latitudes (Ross and Adam 2013). While projections suggest the capacity for some coastal vegetative ecosystems to shift landward in response to sea level rise, adaptive capacity and growth rates may be reduced under higher levels of salinity (Mitra, 2013; Di Nitto *et al.*, 2014). Furthermore, the capacity for coastal habitats to shift landwards may be inhibited by the construction of storm-resilient infrastructure or coastal development (Lynn *et al.*, 2013). Ecosystem phase shifts and trophic cascades have been observed and projected across multiple ecosystems and latitudes, including tropical coral reefs (Inoue *et al.*, 2013; Bell *et al.*, 2013b, Ainsworth and Mumby 2014), tidal marshes (Langley *et al.*, 2013), subtropical ecosystems (Milazzo *et al.*, 2013), temperate ecosystems (Vergés *et al.*, 2014; Wernberg *et al.*, 2013; Thomson *et al.*, 2014), and polar ecosystems (Quartino *et al.*, 2013). [Sections 3.1.1.1, 3.1.1.3, 3.1.1.7, 3.1.2.1, 3.1.2.2, 3.1.3.1]

While AR5 indicated that coral reefs had little scope for adaptation (Wong *et al.*, 2014), recent research has suggested that there may be some capacity for some coral species to recover from climatic shocks and bleaching events (Roff *et al.*, 2014), and to acquire heat resistance through acclimatization (Palumbi *et al.*, 2014). Modeling work indicated that some adaptive responses have already allowed corals to cope with

higher temperatures but the rate of these responses is insufficient to keep up with current GHG emission trajectories (Logan *et al.*, 2013). Moreover, temporary reef refugia have been identified in the western Indian Ocean, Thailand, the southern Great Barrier Reef, central Polynesia (van Hooidonk *et al.*, 2013a), and the Red Sea (Fine *et al.*, 2013), and may be used to assist with ecosystem and species conservation. However, the capacity for coral reefs to respond to multiple stressors remains uncertain (Palumbi *et al.*, 2014), and the primary drivers of changes in net ecosystem calcification have been called into question, with some scientists suggesting that increased dissolution of CaCO₃ could play a greater role than decreased calcification (Eyre *et al.*, 2014). [Section 3.1.2.1]

Studies have increasingly explored synergistic interactions between different climatic drivers, and have found strong variability between impacts to species at different life stages. Simulated ecosystem-based assessments have continued to find theoretical evidence of phase shifts and trophic cascades in coral reef systems arising from synergistic effects associated with multiple stressors—such as deoxygenation, coral bleaching, ocean acidification, and disease—with projected declines in biodiversity and ecosystem services (Ateweberhan *et al.*, 2013; Alva-Basurto and Arias-González, 2014). [Section 3.1.1.3]

Observed and projected climate-induced impacts suggest that sustainable freshwater aquaculture may be more viable than wild-caught fisheries under climate change (Bell *et al.*, 2013a; Rosa *et al.*, 2014; Richards *et al.*, 2015). Increased temperatures are expected to lead to higher growth rates among some cultivated species (e.g., tilapia, carp), while the capacity to control for environmental variables and the likelihood of increased rainfall may yield greater resilience and opportunities for tropical and subtropical aquaculture production (Rosa *et al.*, 2014; Richards *et al.*, 2015). However, changes in the efficiency of aquaculture production associated with an increased prevalence of disease under warmer temperatures are uncertain, and may detrimentally affect human health (Rosa *et al.*, 2014; Himes-Cornell *et al.*, 2013; Rowley *et al.*, 2014). [Sections 3.2.1, 3.2.2]

Increased efforts to characterize and value ecosystem services in the context of climate change, with specific relevance to ecosystem-based adaptation (Lavery *et al.*, 2013; Fanning 2014; Roebeling *et al.*, 2013; Nelson *et al.*, 2013; Spalding *et al.*, 2014). Coastal vegetative habitats have been highlighted as potential means of achieving multiple objectives by combining habitat restoration and climate change mitigation strategies (Nelson *et al.*, 2013; Tokoro *et al.*, 2014; Ross and Adam 2013; Hoegh-Guldberg *et al.*, 2014; Wong *et*

al., 2014). Research continues to focus on the role of coastal habitats in carbon sequestration and storage, supporting the restoration and cultivation of such habitats to aid climate mitigation efforts (Spalding *et al.*, 2014; Duarte *et al.*, 2013) [Section 3.5].

5. CONCLUSION

The literature published subsequent to AR5 strengthens many of the IPCC’s concluding statements regarding climate-related impacts to coastal communities and ecosystems (see Section 4.2), and helps to clarify areas of development, such as the impacts of ocean acidification, the role of genetic and phenotypic adaptation, and the influence of synergistic interactions between climatic stressors (Section 4.1).

While this report illustrates a stronger understanding of biophysical impacts, there is an evident need for an improved understanding of organisms’ and species’ sensitivity to ocean warming and acidification, on the one hand, and of the induced cascading effects within the trophic web, on the other hand. Improved knowledge is also lacking with respect to the values that drive human adaptation and an appropriate approach to framing discussions regarding the impacts of ocean acidification and warming to human societies. Given the inherent role played by humans in climate change—as both the instigators and the victims of environmental change—climate change narratives require explicit connections between the biophysical and human impacts arising from different CO₂-related and anthropogenic drivers, as well as clear options for climate-resilient pathways. In particular, the ethical implications of climate change and ocean acidification need to be addressed: by distinguishing between the ‘experienced’ and ‘imposed’ effects of climate change, for example, Smith *et al.* (2013) highlighted the issue of “climate justice,” or the allocation of responsibility for anthropogenic climate change. This is also applicable to ocean acidification as a global process that will primarily have local impacts. In response, Sovacool (2013) called for a multi-scalar—or polycentric—approach to adaptation to supersede the issue of ethics by distributing action across multiple partners, and thereby allow simultaneous implementation of community- and government-based mitigation and adaptation strategies. As noted in AR5, there is still insufficient translation of scientific evidence into information useful for developing and implementing policies (Wong *et al.*, 2014).

The examples of coastal adaptation highlighted in this report continue to illustrate the benefits of

community-based adaptation through a context-specific understanding of local values, knowledge, and capacity to respond. Ecosystem-based adaptation is increasingly promoted as a feasible, low-cost opportunity for developing nations and marginalized communities to respond to climate change (Hoegh-Guldberg *et al.*, 2014; Magnan, 2014; Wong *et al.*, 2014). However, as noted previously, the rate at which adaptation occurs makes it challenging for scientists to keep pace with developments by publishing in peer-reviewed journals (Noble *et al.*, 2014).

There has been increased demand from policymakers for a shift from detection of climate-related

impacts towards more localized, attribution-based analyses (Parmesan *et al.*, 2013). However, some scientists have argued that sufficient evidence of climate-induced impacts has been obtained through global meta-analyses, and that quantitatively parsing out the contributions of different stressors at each locality would likely yield little additive value due to mismatching spatial and temporal scales and the complex, dynamic nature of ecosystems; rather, they argue that our focus should shift towards implementing existing conservation, adaptation, and mitigation strategies using existing, broad-scale knowledge (Parmesan *et al.*, 2013, Magnan, 2014). ■

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The Oceans 2015 Initiative, Part II

An updated understanding of the observed and projected impacts of ocean warming and acidification on marine and coastal socioeconomic activities/sectors

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