Chapter 30. The Ocean

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Executive Summary

The Ocean plays a central role in Earth's climate, absorbing over 90% of the heat added to the global climate system through the enhanced greenhouse effect. [WGI 3.2] The Ocean is also a major sink for anthropogenic CO_2 emissions. [WGI Box 3.2] Here, we assess the evidence for changes due to anthropogenic climate change (including acidification from rising atmospheric CO_2) on the Ocean as a region. It is *virtually certain* that anthropogenic climate change is already changing ocean temperature and acidity, as well as ocean productivity, trophic structure, and the distribution of species and ecosystems. The world's Ocean, however, encompasses a large variety of oceanographic and ecosystem structures and functions, and, hence, a wide variety of regional responses to climate change. We address this diversity by dividing the Ocean into eight sub-regions: High Latitude Spring Bloom Systems (HLSBS), Eastern Boundary Upwelling Ecosystems (EBUE), Coastal Boundary Systems (CBS), Equatorial Upwelling (EUS), Subtropical Gyres (STG), Semi-Enclosed Seas (SES), the Deep Sea (DS, >1,000 m), and Polar Seas. Dividing the Ocean into these sub-regions takes into account the diversity of marine environments and ecosystems at a large-scale although we acknowledge that any attempt is unlikely to be universally acceptable given the many bases by which this might be done (e.g. ecosystem, biogeochemical). Polar Seas (defined by the presence of sea ice) are not considered here as they are dealt with in Chapter 28. Our assessment reveals widespread impacts on organisms and ecosystems arising from the fundamental changes that have occurred within the physical and chemical conditions of the Ocean (*very high confidence*). Clear attribution of these changes to climate change depends on the sub-region and the physical, chemical or biological components involved. We discuss the implications of observed changes for different ocean sectors and sub-regions as climate change occurs.

The physical and chemical properties of the Ocean have changed significantly over the past 60 years (*very high confidence*). Heat content has increased in the upper layers of the Ocean since 1950 consistent with the positive radiative imbalance of the climate system driven by anthropogenic greenhouse gas emissions. Temperatures in many sub-regions have been influenced by long-term variability (e.g. Pacific Decadal Oscillation, PDO, Atlantic Multidecadal Oscillation, AMO) as well as anthropogenic climate change, with the effects of variability being heightened at regional scales. Regional changes have also occurred in wind speed, surface salinity, ocean currents, solar irradiance, cloud distribution, and oxygen depth profile (*robust evidence, high agreement)*. Thermal expansion and melt water from glaciers and ice-caps have increased sea levels globally and to different extents regionally (*virtually certain)*. Surface warming of the Ocean and changes in wind speed have also increased the thermal stratification of the upper ocean in some regions (*high confidence*). Increased uptake of atmospheric carbon dioxide by the Ocean has decreased ocean pH and fundamentally changed the carbon chemistry of the Ocean *(very high confidence)*. The present state and rate of change of combined ocean pH and the concentration of carbonate ions are unprecedented in millions of years (*robust evidence, high agreement*). [30.3.1, 30.3.2; 6.1.1, 6.2.2.1; WGI 3.2 – 3.8, 10.41-10.4.4]

The Ocean is *virtually certain* to continue to warm and acidify as emissions continue to increase although differences between Representative Concentration Pathways (RCP) are likely to be minimal until 2035 (*high confidence, $p \leq 0.01$*). Projected temperatures of the surface layers of the ocean, however, diverge as the 21st century unfolds and will be 1-3°C higher by 2100 under RCP8.5 than RCP2.6 across most ocean sub-regions. Projected warming beyond 2100, however, is *very likely* to eventually reach average global temperatures and hence ocean temperatures that are 3-11°C above today. Ocean chemistry (pH, carbonate concentrations, and oxygen concentrations) is *virtually certain* to continue changing, with conditions approaching those not seen for 40 million years if atmospheric CO_2 continues to increase in the atmosphere (*very high confidence*). Based on the substantial response of ocean systems to the relatively small amounts of change so far, projected changes in atmospheric greenhouse gas concentrations and temperature are *virtually certain* to drive fundamental and far-reaching changes to the structure and function of ocean ecosystems (*high confidence*), and consequently the goods and services they provide for humanity (*medium confidence*). [30.3.1, 30.3.2, 6.3, 6.4; WGI 3.2, 3.8; Box 3.2, 12.4.7.1, 12.5]

Changes to ocean conditions have resulted in fundamental and extensive changes to organisms and ecosystems in the Ocean. Marine organisms are moving to higher latitudes consistent with warming trends (*high confidence*). Isotherms are migrating rapidly (10-20 km yr^{-1}) across the ocean surface in some regions, especially at lower latitudes causing marine organisms to move, acclimatise, or adapt evolutionarily. The greatest rates of movement of organisms to higher latitudes are seen amongst mobile organisms such as fish, crustaceans and zooplankton assemblages, especially at higher latitudes *(robust evidence, high agreement)*. These changes have also been influenced by diverse factors such as the loss of sea ice, transcontinental shipping and the alteration of coastlines by rising sea levels (*medium evidence, medium agreement*). Increased sea temperatures have also significantly altered the phenology or timing of key life-history events such as plankton blooms, migratory patterns, and spawning in fish and invertebrates over recent decades (*medium confidence*). [30.4, 30.5; 6.2, 6.3, 6.5]

Ocean acidification resulting from the increased flux of atmospheric CO_2 into the Ocean represents a fundamental challenge to marine organisms and ecosystems, although the extent of its influence varies with the taxa and process involved (*high confidence*). The sensitivity of organisms to ocean acidification is highest in the earliest life history stages (*high confidence*). While there is *robust evidence*, *high agreement* and *high confidence* from controlled laboratory experiments and mesocosm studies that ocean acidification significantly impacts a large range of organisms (e.g. corals, fish, pteropods, coccolithophores, and macroalgae), physiological (e.g. skeleton formation, gas exchange, reproduction, growth and neural function) and ecosystem processes (e.g. productivity, reef building and erosion), there are fewer field studies that have shown (or not shown) direct ecosystem changes. Our understanding of synergies and interactions of increased ocean acidification with increased sea temperature is also limited and should be a priority of future studies. [30.3.1, 30.3.2, 30.4, Box CC-OA, 6.2, 6.3, 6.5, Box 5.1, 6.2]

Climate change, by increasing temperatures and altering surface winds, has influenced ocean mixing, nutrient levels and primary productivity. These changes are very likely to have positive consequences for some fisheries and negative ones for others through the de-oxygenation of deep water environment and associated spread of hypoxic zones (*medium evidence, medium agreement*). Changing surface winds have produced major changes in the supply of nutrients to the upper layers of the ocean. In regions where primary production has increased (or is predicted to increase), such as in the High Latitude Spring Bloom Systems (HLSBS), Eastern Boundary Upwelling Ecosystems (EBUE), and Equatorial Upwelling (EUS), energy transfer to higher trophic levels is *likely* to increase along with microbial activity. Increased primary productivity is *likely* to lead to an increased transfer of organic carbon to deep sea habitats stimulating respiration and drawing down oxygen levels in some areas. These changes are further influenced by the contribution of nutrients from coastal pollution, leading to the expansion of hypoxic (low in oxygen) zones in areas such as the Gulf of Mexico, North Sea, Arabian Sea, and coastal areas of many countries. Increasing temperatures will also reduce the solubility of oxygen, adding to oxygen stress (*very high confidence*). [30.5.2, 30.5.4, 30.5.6; 6.2, 6.3, 6.5]

Chlorophyll concentrations have decreased in the STGs in the North Pacific, Indian and North Atlantic Oceans by 9%, 12% and 11%, over and above the inherent seasonal and interannual variability from 1998 to 2010 (*high confidence; $p<0.05$*). Significant warming over this period has resulted in increased water column stratification and reduced mixed layer depth. This has reduced the vertical transport of nutrients into the upper layers of the Ocean and has reduced primary production by phytoplankton in these vast areas (as measured by chlorophyll, see 6.3.1 for associated uncertainties). Reducing primary production is *likely* to impact food availability for pelagic fish species (*limited evidence, medium agreement*). The influence of long-term variability complicates attribution of past changes directly to climate change. Changes in ocean primary productivity, chlorophyll, and other key biogeochemical processes are complex and our understanding how they are likely to change with climate warming is *limited*. [30.5.5.1, Table 30-2, 6.3, 6.1.3, 6.5]

Increasing ocean temperatures are driving a greater frequency of elevated temperature events that have had significant impacts on coastal ecosystems (*very high confidence*). In some cases (e.g. coral reefs, Mediterranean intertidal communities), the projected degradation of these marine ecosystems is *very likely* to pose substantial challenges for coastal societies where livelihood and food security may depend on ecosystem health. Many coastal ecosystems, however, are also affected by a wide range of non-climate change related human activities, making clear attribution of observed changes to climate change difficult. Reducing regional stressors represents an opportunity to strengthen the ecological resilience of these ecosystems which may help them survive projected changes in ocean temperature and chemistry. [30.4, 30.5.3; 30.5.6, 6.2.2.4, 6.3.2, 6.5.2; Box CC-CR]

High Latitude Spring Bloom systems (HLSBS) in the North Eastern Atlantic are changing in response to warming oceans (*high agreement, medium evidence*). These ecosystems are responding to rapid warming, with the greatest changes being observed since the late 1970s in the phenology, distribution and abundance of plankton assemblages, and the reorganisation of fish assemblages. For example, the abundance of boreal species has decreased along the southern fringe and increased along the northern fringe of the HLSBS since cool phase of Atlantic Multidecadal Oscillation (AMO) in the 1960s and early 1970s. However, substantial natural variability over the past 30 years is embedded in the entire Northeast Atlantic region as part of the AMO (WG1 Chapter 14). These changes have both positive and negative implications for the future of the fisheries within the HLSBS. [30.5.1, 30.8.3]

The world's Semi-Enclosed Seas have been changing rapidly since 1982 with projected changes having important ramifications for surrounding countries (*medium confidence*). The upper layers of the world's Semi-Enclosed Seas (SES) show significant warming since 1982, although this warming signal is strongly influenced by long-term variability (e.g. AMO). Further warming is projected which is *very likely* to expose the SES to greater thermal stratification, which will lead *very likely* to reduced oxygen levels at depth and the spread of hypoxic zones, especially in the Baltic and Black Seas. These changes are *likely* to impact regional ecosystems as well as fisheries, tourism, and other human activities although the understanding of the potential impacts is relatively undeveloped. [30.3, 30.5.6]

Evidence that the world's most abundant habitat, the deep sea, is changing is compelling but requires further research (*medium agreement, limited evidence*). Deep sea habitats (>1000 m) occupy 60% of the planet's surface yet are little understood due to the difficulties of accessing them. Deep water coral communities are vulnerable to changes in ocean pH and carbonate chemistry. There is *medium evidence and agreement* that an increased nutrient supply through intensified upwelling in some regions (through intensified upwelling) threatens deep sea ecosystems with hypoxia by increasing the rate of metabolism (and hence oxygen use). Similarly, a decrease in primary productivity in some areas (e.g. subtropical gyres) may reduce the availability of organic carbon to deep sea ecosystems. These changes are *virtually certain* to increase due to the amplifying influence of rising deep water temperatures on microbial metabolism. Our understanding, however, of the changes in deep sea habitats that are currently occurring, and will occur, is limited. [30.5.7, 6.1.1.2, 6.1.1.3]

The observed and projected impacts on ocean ecosystems and processes reveal significant regional differences that will require differing policy responses and adaptation approaches (*medium agreement, medium evidence*). Changes to the distribution and abundance of fish species as waters warm and acidify will dictate the need for flexible and informed decision-making. For example, tuna, a key fisheries species, are highly sensitive to changes in sea temperature and changes in their distribution and abundance will provoke new technological and policy challenges. The cross-boundary migration of fish stocks (from the waters of one nation to another) will require international cooperation and evidence-based decision making. [30.5.5.2, 30.6.3]

Projected change to ocean ecosystems as a result of ocean warming and acidification will reduce access to food, and increase poverty and disease in many countries (*medium agreement, limited evidence*). Key fisheries throughout the world are being impacted by climate change, through direct physiological and ecological impacts. In many parts of the world (particularly in the tropical and subtropical regions), fisheries are in decline and will continue to do so under rapid anthropogenic climate change. Reduced access to food in some coastal regions as a result of declining fisheries will expose greater numbers of already vulnerable people to reduced access to food and will result in associated health impacts. Disease, impacts of harmful algal blooms, cholera, and ciguatera poisoning are also *likely* to increase as oceans warm and acidify. Understanding of these changes and their origin is important although limited. [30.6.3, 30.6.5]

Building dynamic fisheries management as well as sustainable aquaculture represent opportunities for adaptation to changes in the distribution and productivity of fish stocks (*high agreement, medium evidence*). The application of ecosystem-based management which includes climate change to manage the development and maintenance of fish stocks represents a key tool for adapting to changes resulting from climate change. Reducing non-sustainable fishing (e.g. bottom trawling, 'ghost' fishing) provides an avenue for adapting to climate impacts by reducing the impact of additional stressors. Changes to coastal fishing due to the loss of coastal ecosystems will require adaptation strategies such as marine protected areas, alternative livelihoods and/or the movement of people and industry sectors. Industries such as nature-based tourism will require similar strategies for decision-making. [30.6.3, 6.5, Ch7]

Changes to surface winds, sea level, wave height and storm intensity will increase the risks associated with coastal and ocean-based industries such as shipping, oil, gas and mineral extraction (*medium agreement, medium evidence*). Storm impacts on coastal areas will increase with sea level rise through greater storm surge impacts. [WGI, 3.7.4] Strategies will require consideration of these changes in the design and use of ocean-based infrastructure together with the evolution of policy for reducing risks to equipment and people. New opportunities for shipping, oil, gas and mineral extraction, as well as international issues over access and vulnerability, are likely to evolve as waters warm, particular in high latitude regions. [30.6, 6.5]

Adapting to the impacts of climate change within the Ocean is poorly developed but will benefit from improved forecasting and early warning systems (*medium agreement, limited evidence*). Given the reduced opportunity to mitigate ocean warming and acidification directly due to the scale of the problem, adapting fisheries strategies based on forecasting as well as developing ecosystem-based management strategies for fish stocks will help sustain many fisheries under climate change to some extent. Similarly, advanced warning systems can be used to help modify aquaculture management such as treating inflowing water to facilities during periods of low pH. While some examples exist of adaptation along these lines, the options are poorly developed for the broader set of impacts from climate change. [30.6]

Ocean ecosystems and associated sub-regions offer a large potential for carbon dioxide mitigation strategies (*medium agreement, limited evidence*). Ecosystems such as mangroves, seagrass and salt marsh represent potentially significant carbon sequestration strategies (e.g. 'blue carbon'). Reducing highly anoxic habitats through coastal restoration (and hence the emission of methane) also represent significant mitigation opportunities, although an understanding of these opportunities is limited. [30.7] There are also significant opportunities for ocean-based industries such as international shipping to continue to reduce their emissions intensity, as well as projects that source offshore wind and tidal power. Sequestration of anthropogenic CO_2 into deep ocean areas has been explored although studies indicate significant hurdles with respect to the expense and vulnerability of deep water marine ecosystems.

International frameworks for decision-making and collaboration represent vital tools for anticipating and responding to impacts of global climate change (including ocean acidification) on marine systems. UNCLOS, LOSC and other international frameworks provide the common basis for countries to recognise the common challenges arising from the impact of climate change on the ocean and to solve problems as diverse as creating sustainable fisheries across national borders, collaborative responses to the impacts of extreme events, and strengthening international food security through sustainable marine resources. Given the importance of the ocean to all countries, there is a need for the international community to progress rapidly to 'whole of ocean' strategies for responding to the challenges associated with anthropogenic climate change.

30.1. Introduction

The Ocean exerts a profound influence on the Earth, interacting with its atmosphere, cryosphere, land and biosphere to determine planetary conditions. It also directly influences human welfare through the provision and transport of food and resources, as well as cultural and economic benefits, and indirectly through the regulation of atmospheric gas content and distribution of heat and water across the planet. The present chapter evaluates the current impacts and future implications for Ocean sub-regions of increased concentrations of atmospheric greenhouse gases and other anthropogenic alterations to planetary radiative forcing. We also include the influence of changes to the chemistry of the Ocean through its acidification by increasing atmospheric carbon dioxide concentrations. In doing so, this chapter assesses recent scientific evidence and examines the extent to which significant changes can be accurately detected and attributed to anthropogenic climate change. The impacts, risks and vulnerabilities associated with climate change are assessed within seven ocean sub-regions, and the impacts and adaptation options for key ocean-based sectors discussed. Polar oceans are not directly considered here as they are given detailed treatment elsewhere (WGII Ch28). It is also noteworthy that while the impact of climate change on ocean sub-regions directly influences the coastal and low-lying sub-regions of multiple nations, a detailed discussion of these potential impacts also occurs in the relevant chapters of this report (e.g. WGII Ch5, Ch29).

30.1.1. Major Sub-Regions within the Ocean

The Ocean represents a vast region which stretches from the high tide mark to the deepest oceanic trench (11,030 m), and occupies 71% of the earth's surface. There are considerable challenges in assessing the regional impacts of climate change on the Ocean. Not only is the Ocean vast but it also contains a very broad diversity of life forms and habitats, many of which are poorly documented and not easily studied due to the difficulty of visiting much of this enormous region. Devising an appropriate structure in order to explore the influence of climate change on the entire ocean system is consequently challenging. *Longhurst* [1998] identified over 50 distinct ecological provinces in the ocean, defined by physical forcing, and the structure and function of phytoplankton communities. Longhurst's scheme, however, yields far more sub-regions than could be sensibly discussed in the space allocated here. Consequently, we have used comparable principles but have divided the non-polar ocean into seven larger sub-regions similar to *Barber* [1988]. In this case, our sub-regions are unified by specific physical forcing and ecosystem structure that might be expected to respond to climate change in broadly distinct ways (Figure 30-1, Table 30-1). We recognize that these sub-regions do not always map perfectly over physical-chemical patterns or specific geographies, and that they interact with strongly with terrestrial regions through weather systems and the exchange of materials. We also recognize that different ocean sub-regions may have substantially different primary and fishery productivities. Notably, over 80% of fisheries production is associated with three ocean sub-regions Northern hemisphere High Latitude Spring-bloom (HLSBS), Coastal Boundary Systems (CBS), and Eastern Boundary Upwelling Ecosystems (EBUE; Table 30-1, Figure 30-1B). The Deep Sea (>1,000m) is included as separate category which overlaps the six other ocean sub-regions.

[INSERT FIGURE 30-1 HERE
Figure 30-1: A. The world's non-polar oceans have been separated into seven major sub-regions, with polar oceans being excluded due to treatment elsewhere (Ch28). The chlorophyll concentration averaged over the period from Sep 1997 – 30 Nov 2010 (NASA) is also shown. Together with key oceanographic features, primary production was the basis for separating the ocean into the sub-regions shown. The map insert shows the distribution of Deep Sea habitat (>1000 m; Bathypelagic and Abyssopelagic habitats combined). Numbers refer to: 1 = High Latitude Spring Bloom Systems (HLSBS), 2 = Equatorial Upwelling (EUS), 3 = Semi-enclosed seas (SES), 4 = Coastal Boundary Systems (CBS), 5 = Eastern Boundary Upwelling Ecosystems (EBUE), 6 = Subtropical gyres (STG), and 7 = Deep sea (>1000 m). B. relationship between fish catch and areas for Ocean sub-regions shown in A. Red columns: average fish catch (millions tons yr^{-1}) for the period 1970-2006. Blue columns: area (millions km^2).]

[INSERT TABLE 30-1 HERE
Table 30-1: Percent area of the ocean, primary productivity and fisheries catch (production) for major sub-regions of the ocean (for location of sub-regions, see Figure 30-1).]

30.1.2. Detection and Attribution of Climate Change within the Ocean

The primary goals of Chapter 30 were to assess recent literature with respect to the detection and attribution of climate change to the physical, chemical and biological components of the Ocean and its sub-regions. Within Chapter 3 of IPCC AR5 from Working Group I (WGI), detailed observations of changes to the physical and chemical characteristics of the Ocean are described, while Chapter 10 assesses the influence of anthropogenic climate change on ocean heat content, ocean salinity on freshwater fluxes, sea level, and oxygen (WG1 10.4). These observations are assessed relative to near and long-term projections generated by CMIP5 models (WGI Chapters 11-12). We extend assessment to the observed changes in the physical and chemical characteristics of the Ocean in response to anthropogenic climate change by assessing change on Ocean sub-regions.

Attribution follows the detection of a change by addressing the question as to whether climate change has significantly contributed to the observed change [18.2.1.1]. We attempt to do this for a wide range of changes within our defined sub-regions within the Ocean. There are a number of general limitations to the detection and attribution of impacts to climate change (including ocean acidification) that are discussed elsewhere [18.2.1.2]. Challenges with respect to ocean temperature and heat content, acidification, salinity, sea level, and oxygen are dealt with in Chapter 10 (WGI). Generally, attribution to climate change occurs when the full range of possible forcing factors is considered and those related to climate change are found to be the most likely explanation for the change in question. Comparing detected changes to the expectations of well-established scientific evidence plays a central role in the successful attribution of detected changes. Approaches and 'best practice' guidelines are discussed in Chapters 10 and 18 (WGI), as well as several other places [*Hegerl et al.*, 2010; *Hegerl and Zwiers*, 2007; *Stott et al.*, 2010].

Achieving successful detection and attribution of recent changes in ocean systems is complicated, as is the case on land, by the influence of sources of long-term and complex variability such as the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO). The fragmentary nature of ocean observing, uncertainty of model simulations, and confounding influences of anthropogenic factors unrelated to climate change represent significant challenges [*Hoegh-Guldberg et al.*, 2011a; *Parmesan et al.*, 2011]. Anthropogenic climate change (e.g. ocean warming and acidification) are co-mingled with other human driven changes (e.g. pollution, introduced species, overexploitation of fisheries, and disease, [*Halpern et al.*, 2008] thereby frustrating efforts to establish a clear climate change signal. Long-term records are essential for this task but are rare, especially in difficult to access oceanic environments. Stressors not related to climate change may also interact synergistically or antagonistically with each other and climate change, further vexing the process [*Hegerl et al.*, 2010; *Hegerl and Zwiers*, 2007].

30.2. Major Conclusions from Previous Assessments

An integrated assessment of the impacts of climate change on the Ocean as a region was not done during previous IPCC assessment reports, although a chapter devoted to the Ocean in the Second Assessment Report (SAR) did "attempt to assess the impacts of projected regional and global climate changes on the oceans" [*Ittekkot et al.*, 1996]. Notwithstanding, attempts to detect and attribute the impact of climate change on observed changes in ocean and coastal systems are spread throughout previous assessment reports, reducing an key opportunity to synthesize the physical, chemical and biological changes and their causes within the Ocean and its sub-regions. The IPCC Fourth Assessment Report (AR4) concluded, however, that while terrestrial sub-regions are warming faster than the oceans, "Observations since 1961 show that the average temperature of the global ocean has increased to depths of at least 3,000 m and that the ocean has been taking up over 80% of the heat being added to the climate system." AR4 also concluded that sea levels had risen due to the thermal expansion of the ocean but recognized that our understanding of the dynamics of glaciers and ice sheets was "too limited to assess their likelihood or provide a best estimate or an upper bound for sea level rise" (AR4 SPM).

Changes to ocean temperature and density also have the potential to alter large-scale ocean circulation. AR4 concluded, however, with respect to the Meridional Overturning Circulation (MOC) that "it is very likely that up to the end of the 20th century the MOC was changing significantly at interannual to decadal time scales" (AR4 WGI, CH5, Box 5.1), although definitive evidence of a slowing MOC was lacking. According to AR4, "sea-level rise over the last 100 to 150 years is probably contributing to coastal erosion in many places" including the east coasts of the United States and United Kingdom (AR4, WGII Chapter 1). The AR4 assessment was *virtually certain* (Table 7.3), however, that rising atmospheric CO_2 had changed ocean chemistry (buffering, carbonate), and that a decrease in surface pH of 0.1 had occurred over the global ocean, which was calculated from the uptake of anthropogenic carbon estimated to have occurred between 1750 and 1994 [*Raven et al.*, 2005; *Sabine et al.*, 2004] ; AR4, 5.4.2.3].

Large-scale changes to ocean salinity were also observed from 1955 to 1998, which were "characterised by a global freshening in sub-polar latitudes and salinification of shallower parts of the tropical and subtropical oceans" (AR4 WGI Chapter 5). In this case, freshening was observed in the Pacific, with increased salinity being observed in the Atlantic and Indian Oceans (AR4, WGI, and ES). These changes in surface salinity were qualitatively consistent with observed and expected changes to surface freshwater flux. Freshening of mid- and high-latitude waters together with increased salinity at low latitudes were seen as evidence "of changes in precipitation and evaporation over the oceans".

Substantial evidence indicated that changing ocean conditions have extensively influenced marine ecosystems (AR4, WGI, Table 1.4). The abundance and productivity of pelagic plankton assemblages have responded to regional changes in sea temperature, stratification, upwelling, iron deposition, and other physical and chemical changes [*Hayes et al.*, 2001]. Changes in the distribution and timing of reproduction were also reported in a range of organisms, although a separate detection and attribution of changes to climate change (from terrestrial studies) was not done as part of AR4. AR4 noted that there is an "accumulating body of evidence to suggest that many marine ecosystems, including managed fisheries, are responding to changes in regional climate caused predominately by warming of air and sea surface temperatures (SSTs) and to a lesser extent by modification of precipitation regimes and wind patterns".

Observed changes in marine ecosystems and managed fisheries within AR4 included: changes to plankton community structure and productivity, pelagic phenology and biogeography, intertidal communities along rocky shores, kelp forests, and the distribution of pathogens and invasive species. Changes were also observed in coral reefs through increased mass coral bleaching and mortality, populations and biogeography, migratory patterns and trophic interactions of sea birds, marine reptiles and mammals, as well as a range of other marine organisms and ecosystems (AR4, WGII, Table 1.5).

30.3. Recent Changes and Projections of Ocean Conditions

Understanding the extent to which the physical and chemical environments of the Ocean and its sub-regions have changed is centrally important to the interpretation of how organisms and ecosystems are likely to change over the coming decades and century. Increasing concentrations of atmospheric CO_2 have increased average global temperature and subsequently the temperature of the Ocean, and have fundamentally altered its chemistry (AR5, WGI, Executive Summary). Expert archives such as HadISST1.1 contain sea surface temperature (SST) from a range of sources allowing an opportunity to explore monthly mean gridded, global SSTs from 1870 to present [*Rayner et al.*, 2003]. The HadISST1.1 data set is used here to investigate regional trends in SST within six of the seven sub-regions (Table 30-1), along with a range of other expert data sets for other variables including sea level, wind speed, water movement, water column structure, oxygen concentration, biogeochemistry and salinity.

30.3.1. Physical Changes

30.3.1.1. Heat Content and Temperature

There is little disagreement that Ocean has been dominant sink for most (>90%) of the extra heat arising from the human influence on Earth's radiative balance (*virtually certain;* WGI Box 3.1). As a result, the upper layers of the Ocean (0-75 m) have warmed significantly (>0.1°C per decade) since global observations became available (*virtually certain*). The intensification of the warming signal is associated with an increased thermal stratification of the upper layers (0-200 m) of the Ocean of around 4% over a 40-year record. These changes have a significant (*virtually certain*, $p < 0.01$) anthropogenic signal [*Gleckler et al.*, 2012]**.** Rates of warming decrease to 0.015°C per decade at 700 m and are likely to be small but positive at deeper depths (<0.01°C per decade; WGI 3.2.2, Figure 3.1). All three ocean basins are warming at rates that exceed that expected if there were no changes to greenhouse gas forcing over the past century (Figure 3.2).

We use published HadISST 1.1 to explore trends in historic SST with our sub-regions outlined in Figure 30-1. The .2median SSTs for 1871-1995 from the Comprehensive Ocean-Atmosphere Data Set (COADS) were merged with data from the Met Office Marine Data Bank (MDB) to produce monthly globally-complete fields of SST on a 1° latitude-longitude SST grid from 1870 to date. The higher resolution HadISST 1.1 dataset (as compared to HadSST3) is best suited for use in this chapter.

The surface waters of the three ocean basins are warming similarly, with the Atlantic Ocean warming faster (0.3°C decade^{-1}), than the Pacific (0.20°C decade^{-1}) and Indian (0.11°C decade^{-1}) Oceans (Figure 30-2). All but one of the Ocean sub-regions (exception being SES) have warmed significantly over the period 1950-2009 (HadISST1.1 data,

Table 30-2) although trends in temperature vary at a finer scale (e.g. South versus North Pacific, Table 30-2, Figure 30-3A). Notably, the southern portions of the HLSBS also did not show significant warming over this period although the northern hemisphere HLSBS did (Table 30-2). The rates of warming observed for the North Atlantic are consistent with the analysis of Advanced Very High Resolution Radiometer (AVHRR) satellite data combined with *in situ* measurements from ships and buoys collected in the International Comprehensive Ocean–Atmosphere Data Set (ICOADS, icoads.noaa.gov)[*González-Taboada and Anadón*, 2012]. Among the Eastern Boundary Currents, the Canary and Californian currents exhibited significant warming (0.09°C.decade^{-1} and 0.12°C.decade^{-1} respectively; $p < 0.05$) while the Benguela and Humboldt currents did not show significant temperature changes ($p > 0.05$; Table 30-2). The Coastal Boundary Systems showed highly significant warming (from 0.09°C.decade^{-1} to 0.13°C.decade^{-1}, Table 30-2). All subtropical Gyres (except the North Atlantic sub-tropical gyre) exhibited significant warming although rates were lower than analyses done over shorter periods (e.g. 1998 to 2010 [*Signorini and McClain*, 2012] and based on NOAA_OI_SST_V2 data (Figure 30-12B). Trends from 1950-2009 were not significant within the five SES analyzed here, although studies done of shorter periods (e.g. 1982-2006, [*Belkin*, 2009] reveal significant increases in SST temperature of: Baltic (1.35°C), Black (0.96°C), Red (0.74°C) and Mediterranean (0.71°C) Seas. These more recent and shorter length studies are complicated by the influence of patterns of long-term variability, most probably influenced by their small and land-locked nature. Given the large sensitivity of coral reefs to temperature anomalies [*Eakin et al.*, 2010; *Strong et al.*, 2011], we also examined the temperature trends in key coral reef regions using the World Resources Institute's Reefs at Risk (www.wri.org) to identify HadISST1.1 grid cells containing coral reefs (Figure 30-4). Grouping the results into six major coral reef regions, we found that coral reef waters had increased in temperature over the 50 year period examined by 0.36-0.65°C (Table 30-2).

[INSERT FIGURE 30-2 HERE
Figure 30-2: Observed and simulated variations in past and projected future annual average sea surface temperature over various oceanic regions. The black line shows estimates from HadISST1 observational measurements. Shading denotes the 5-95 percentile range of climate model simulations driven with "historical" changes in anthropogenic and natural drivers (62 simulations), historical changes in "natural" drivers only (25), the "RCP4.5" emissions scenario (62), and the "RCP8.5" (62). Data are anomalies from the 1986-2006 average of the HadISST1 data (for the HadISST1 time series) or of the corresponding historical all-forcing simulations. Further details are given in Box 21-3.]

[INSERT FIGURE 30-3 HERE
Figure 30-3: Analysis of data from Hadley Centre (HadISST 1.1, [*Rayner et al.*, 2003]) for different ocean sub-regions. A. Rate of change in sea surface temperature over the past 30 years (°C. decade^{-1}). B. Velocity at which isotherms are moving (km.decade^{-1}) from 1960-2009. C. Shift in seasonal changes that drive natural history events (days.decade^{-1}) for April and D. for October. E.]

[INSERT FIGURE 30-4 HERE
Figure 30-4: Location of coral reef grid cells used in Tables 30.2 and 30.4 as well as in Figure 30-11. Each dot is centred over a 1x1 degree grid cell within which lies at least one coral reef. The latitude and longitude of each reef is derived from data provided by the World Resources Institute's Reefs at Risk (http://www.wri.org). The six regions are as follows: Red – Western Pacific; Blue – Eastern Pacific Ocean; Green – Caribbean & Gulf of Mexico; Yellow – Western Indian Ocean; Magenta – Eastern Indian Ocean; and Cyan – Coral Triangle & SE Asia.]

[INSERT TABLE 30-2 HERE
Table 30-2: Regional changes in sea surface temperature (SST) over the past 50 years for ocean sub-regions specified in Figure 30-1. A linear regression was fitted to all 1x1 degree monthly SST data extracted from the HadISST 1.1 data set (Rayner et al., 2003) for the period of 1950 to 2009 for each ocean sub-region. The Table includes the slope of the regression (ºC.decade^{-1}), p value of the slope being different to zero, Linear Change Over 50 Years (slope of linear regression multiplied by 5 to obtain the average change over 50 years, and the difference between the mean temperature (1950-1959) from the mean temperature 50 years later (2000-2009). The latter may be different to the linear change over 50 years if there is significant long-term variability around the trend line. The last column compares the linear trend with that calculated between the two means with significant deviations (<0.8 and > 1.2) shown in red. P values that exceed 0.05 are also shown in red.]

Burrows et al. [2011] examined the rate at which isotherms are migrating by calculating the ratio of the rate of temperature change (°C.year^{-1}) to the spatial gradient of temperature (°C.km^{-1}) over the period 1960-2009. Given the essential role that temperature plays in the biology and ecology of marine organisms [*Poloczanska et al*., 2013; *Pörtner*, 2002], the speed of isotherm migration ultimately determines the speed at which populations must either move, adapt, or acclimatize to changing sea temperatures [*Burrows et al*., 2011; *Hoegh-Guldberg*, 2012b; *Pörtner*, 2002]. This analysis and others (e.g. North Atlantic, *González-Taboada and Anadón* [2012]) reveals that isotherms are moving at high velocities (up to 20 km.yr^{-1}) across the ocean, especially at lower latitudes (Figure 30-3B; *high confidence*). Other sub-regions showed lower velocities with contracting isotherms (cooling) in some areas (e.g. the Central and North Pacific, and Atlantic, Oceans Figure 30-3B). There are also changes in the timing of seasonal temperature in both spring and fall/autumn (Figure 30-3 C, D). The timing of spring conditions has advanced by 2-5 day.decade^{-1} in many parts of the global ocean, although the extent of change varies geographically. These changes in thermal environments are likely to have impacts on a range of different biological processes including the migration of species to higher latitudes and the timing and synchrony of reproductive and other seasonal behaviors [*Burrows et al*., 2011; *Poloczanska et al*., 2013], although it is noteworthy that other variables (e.g. light, food, habitat) can play significant roles in determining the distribution and abundance of marine organisms.

Significant excursions of sea temperature above long-term summer temperature maxima (or below long-term temperature minima) have significant impacts on marine organisms and ecosystems [*Bensoussan et al*., 2010; *Crisci et al*., 2011; *Harley*, 2011; *Hoegh-Guldberg*, 1999]. Consequently, calculating heat stress as a function of exposure time and size of a particular temperature anomaly has proven useful in understanding recent changes to organisms and ecosystems [*Strong et al*., 2011]. The total heat stress accumulated over the period 1981-2010 was calculated using the methodology of [*Donner et al*., 2007] and a reference climatology based on 1985-2000 in which the highest monthly SST was used to define the thermal threshold, above which accumulated thermal stress was calculated as 'exposure time multiplied by stress' or Degree Heating Months (DHM). Thermal stress was calculated as the running total of four consecutive months. While most sub-regions of the ocean experienced an accumulation of heat stress (relative to a climatology based on the period 1985-2000), equatorial and high latitude sub-regions in the Pacific and Atlantic oceans have the greatest levels of the accumulated heat stress (Figure 30-5A). There was also a higher proportion of years that had had at least one stress event (DHM > 1) in the last 30 years (1981-2010) than in the preceding 30 years (1951-1980; Figure 30-5B). In the last 30 years, most sub-regions that have coral reefs have experienced heat stress sufficient to cause mass coral bleaching [*Strong et al*., 2011] events every 2-3 years.

[INSERT FIGURE 30-5 HERE
Figure 30-5: Recent changes in thermal stress calculating using HadISST 1.1 data. A monthly climatology was created by averaging the HadISST monthly SST values over the period 1985-2000 to create twelve averages, one for each month of the year. The Maximum Monthly Mean (MMM) climatology was then created by selecting the hottest month for each pixel. Anomalies were then created by subtracting this value from each SST value, but only allowing values to be recorded if they were greater than zero (Donner et al., 2007). Three measures of thermal stress change were then created: (A) Total thermal stress for the period 1981-2010, calculated by summing all monthly thermal anomalies for each grid cell. (B) Proportion of years with thermal stress, which is defined as any year that has a thermal anomaly, for the periods 1951-1980 and (C) 1981-2010.]

Projections of future sea temperature changes were examined using ensemble averages from AOGCM simulations available in the CMIP5 archive (Table 30-3) for the four representative concentration pathways (RCP2.6, RCP4.5, RCP6.0, and RCP8.5; [*van Vuuren et al*., 2011]). Ensemble averages for each RCP are based on simulations from 10 to 16 individual models (Table 30-3). Model hind-cast changes matched those observed for Ocean sub-regions for the period 1980-2009 (HadSST 1.1, Table 30-2, Figure 30-2), with the model ensemble slightly overestimating the extent of change across the different Ocean sub-regions (slope of observed/model = 0.81, $r^2 = 0.76$, $p < 0.001$). In this way, the absolute amount of change projected to occur in the ocean sub-regions was calculated for near-term (2010-2039) and long-term (2070-2099) periods (Table 30-4). In the near term (2010-2039), changes in the temperature projected for the surface layers of the ocean are largely indistinguishable between the different RCP pathways due to the similarity in forcing until 2035. By the end of the century, however, SSTs across the Ocean sub-regions were 1-3°C higher under RCP8.5 than those projected to occur under RCP2.6 (Table 30-4). The implications of these projected changes on the structure and function of oceanic systems are discussed in later in this chapter.

[INSERT TABLE 30-3 HERE
Table 30-3: CMIP-5 models used to create the Chapter 30 RCP 2.6, 4.5, 6.0 and 8.5 SST ensembles.]

[INSERT TABLE 30-4 HERE
Table 30-4: Projected changes in sea surface temperature (SST, ºC) over the next 90 years for Ocean sub-regions (Figure 30-1) using model runs from the Coupled Model Intercomparison Project Phase 5 (CMIP-5, http://cmip-pcmdi.llnl.gov/cmip5/). Runs were divided up into their respective Representative Concentration Pathways (RCP) to form four groups; RCP2.6, RCP4.5, RCP6.0 and RCP8.5. The CMIP-5 models that were used in this analysis are listed in Table 30-3. For each region, a linear regression was fitted to all 1x1 degree monthly SST data extracted from the models for each of three periods; 2010-2039, 2040-2069 and 2070-2099. The average change in SST was calculated by multiplying the slope of each linear regression by 360 (months) to derive the average change over each successive 30 year period. The table is divided into two sections, "Near-term (2010-2039)" – the average change in SST over the next 30 years, and "Long-term (2010-2099)" – the total change from 2010-2099, which was calculated by adding the average change of the three 30 year periods from 2010 to 2099. This is a simplified method to account for slight non-linearity in SST change over the 90 year period.]

30.3.1.2. Sea Level

The Ocean has expanded as a result of its increased heat content (3.7.2) and has expanded in mass (reliable records begin in 2002) mainly as a result of water being added from melting glaciers and ice sheets on land. As a result of the thermosteric and mass components, it is *virtually certain* that Global Mean Sea Level (GMSL) has increased between 1.4 and 2.0 mm yr^{-1} over the 20th Century and between 2.7 and 3.7 mm yr^{-1} since 1993 [(99% confidence; WGI 3.7.6]. It is also considered *very likely* that sea level rise has accelerated over the past two centuries and that rates are tenfold higher than the relatively high rates that occurred during the late Holocene [WGI Chapter 3, Chapter 5, 13.2.1–2, Figure 13.3].

Measurement of sea level rise using satellite altimetry, oceanographic buoys and floats (e.g. Argo Program) and tidal gauges reveal that sea level rise varies geographically, with rates three times higher than the global average sea level rise in the Pacific Warm Pool (PWL) located in the Western Pacific and South-East Asian region, and rates that are close to zero in many parts of the eastern Pacific. The high rates of sea level rise associated with the PWL are a result of the intensification of trade winds while the lower rates of sea level rise in the western United States are associated with changes in wind stress, both of which are strongly influenced by PDO variability (WGI 3.7.3, Figure 3.11 and FAQ 13.1). These differences are expected to vary on decadal timescales although it is very likely (*high confidence*) that 95% of the Ocean will experience significant regional changes in sea level over and above this source of variability (WGI Section 13.6.5, Figures 13.15–13.17).

Global Mean Sea Level is likely to increase by 0.7 m to 0.95 m by 2100 for Representative Concentration Pathways (RCP) of 2.6 and 8.5, respectively (*medium confidence*). Semi-empirical approaches project that sea level will increase well above 1 m by the end of the century (up to 1.5 m, WGI Table 13.6) although there is some discussion around assumptions associated with these approaches (WGI 13.4.1, 13.4.5). It is significant to note that sea level rise under these scenarios does not stop at 2100 and continues to occur for hundreds of years into the future, depending on the scenario in question. Central to this analysis is the millennial scale commitment to further sea level rise that is likely to arise from the melting of the Greenland and Antarctic ice sheets.

The combined effects of sea level rise and other factors such as increased storm intensity are very likely to increase the occurrence of extreme flooding events (WGI 13.7.2, 18 Figure 13.19). Regional flood risk depends on local topology, oceanography and other factors. While complete understanding of the associated risks is relatively undeveloped, significant coastal and low-lying areas, particularly in the Pacific Ocean and North Atlantic, face increased in flood risk (5.5). Future impacts from sea level rise include increasing penetration of storm surge into coastal areas, changing patterns of shoreline erosion (5.2.2.1) as well as the inundation of saltwater into coastal aquifers (5.3.2.2.). While habitat may be lost, some examples of habitat expansion have been reported [*Brown et al.*, 2011]. Overall, changes to sea level and storm intensity are very likely to modify the habitats and hence coastal ecosystems such as beaches, salt marsh, coral reefs and mangroves (5.4.1.5), especially where rates of sea level rise are highest (e.g. South East Asia and the Western Pacific).

30.3.1.3. Surface Wind and Ocean Circulation

Atmospheric and ocean circulation (and their interaction) are centrally important to the chemical, physical and biological characteristics of the Ocean, determining crucial properties such as intensity of ocean ventilation, coastal upwelling, primary production, carbon export, and the spatial distribution and trophic interaction of plankton populations. While water is the major conveyor for transporting nutrients to land plants, the critical factor for transporting nutrients to the marine primary producers is ocean mixing driven by wind. Wind stress measurements from satellite and *in situ* observations have been collated within a number of international projects to produce reliable data sets on historic global wind patterns. In addition to an expanding set of ocean observing systems (e.g. Global Drifter and Argo Programs), there is a smaller archive of ocean circulation measurements, the small size of which ultimately limits our understanding of how ocean circulation has changed (WGI 3.6).

The National Center for Environmental Prediction (NCEP) Reanalysis Project, [*Kalnay et al.*, 1996] provides an opportunity to explore regional changes that have occurred over the past 60 years (1951-2010, Figure 30-6). While there are large uncertainties associated with historic wind speed data generally (WGI 2.7.2) and overall confidence in wind trends is low (SREX 3.3), there are some specific trends that persist across multiple data sets and analyses. Wind stress (westerly winds) has increased since 1951 over the Southern Ocean (Figure 30-6A) which matches observations from satellites and island station data since the early 1980s (*medium confidence*, WGI 3.4.4). A progressive migration of the westerlies towards higher latitudes has also occurred over the past several decades [*Cai*, 2006.; *Cai and Cowan*, 2007]. These changes are affecting mixed-layer dynamics, nutrient flux, and ocean circulation. The transport of Indian Ocean waters into the South Atlantic has increased in response to latitudinal shifts in the Southern Hemisphere westerlies [*Bard and Rickaby*, 2009; *Biastoch et al.*, 2008a; *Biastoch et al.*, 2008b], with potential implications for the evolution of the MOC [*Friocourt et al.*, 2005] and consequently future climate.

Surface waves are influenced by wind stress although understanding trends remains a challenge due to the paucity of data sets. It is likely, however, that Significant Wave Height (SWH) has been increasing since the 1950s over the Southern Ocean (up to 5% per decade, WG1 3.4.6) and mid-latitudes of the North Pacific and Atlantic Oceans (winter season trends of 8-20 cm per decade; WGI 3.4.6, 2.7.2). Understanding how SWH will change over the coming decades and century remain *uncertain* over most of the ocean remains an important knowledge gap (WG1 3.4).

Parts of the tropical Pacific show a decrease in wind stress over the same period (Figure 30-6A) which is consistent with other studies [*Vecchi et al.*, 2006] and analyzes (WGI Figure 2.37). Reduced trade wind speed is consistent with Walker Circulation and appears to have a considerable anthropogenic forcing component [*Vecchi et al.*, 2006]. Winds speeds have increased within some Eastern Boundary Upwelling Systems (e.g. California Current, Figure 30-6A; WG1 2.7.2). Changing wind regimes have the potential to influence Mixed-Layer-Depth (MLD) and upwelling intensity in highly productive sub-regions of the world's oceans although agreement is low as to whether or not upwelling will intensify across all areas [*Bakun*, 1990; *Bakun et al.*, 2010]. While there are many uncertainties with how wind stress will change under future changes to global climate, evidence from the tropical Pacific is consistent with predictions of further weakening of tropical atmospheric circulation under the influence of anthropogenic forcing [*Vecchi et al.*, 2006]. These changes are closely linked to patterns (and are likely to influence) of long-term variability associated with ENSO, NAO and SAM although observations are too limited in space and time to be able to separate anthropogenic trends from natural variability (WGI 3.5).

There is growing evidence that major circulation systems have changed. It is very likely, for example, that the subtropical Gyres (STG)s within the three ocean basins have expanded and strengthened since 1993 (WGI 3.5), and it is *as likely as not* that these changes are associated with an anthropogenic driver [*Signorini and McClain*, 2012].

There is *limited evidence* for other large-scale trends in major features of ocean circulation (e.g. Atlantic Meridional Overturning Circulation, AMOC, Indonesian flow-through) at this point (WGI 3.6). Global climate models need firstly to capture the large-scale changes in wind in order to accurately predict changes in primary production. Primary production, however, is also strongly dependent on regional and local processes down to frontal and eddy-forming scales implying that high resolution predictions of wind stress are also needed and represent an essential knowledge gap.

30.3.1.4. Solar Radiation and Clouds

Solar radiation plays a crucially important role in the biology of marine organisms. Not only as a source of energy for photosynthesis but it is also as a potential co-stressor in temperature related stress such as seen during mass coral bleaching and mortality events [*Hoegh-Guldberg*, 1999]. Global surface solar radiation (from the NCEP/NCAR Reanalysis Project, *Kalnay et al*. [1996]) decreased 4.3 $W.m^{-2}decade^{-1}$ from the 1950s until 1991 after which it increased at 3.3 $W.m^{-2}decade^{-1}$ until 1999 [*Ohmura*, 2009; *Wild*, 2009]. Changes in solar radiation and cloudiness from 1951 to 2010 vary regionally (Figure 30-6 B, C). The largest increases in solar radiation and decreases in cloudiness from 1951 to 2010 occurred in the tropical Pacific. These observations are consistent with the eastward shift in tropical convection and total cloud cover from the western to central equatorial Pacific over the 20th Century and with the long-term weakening of the Walker circulation (WG1 2.5.7.3). Decreases in cloud cover from 1951 to 2010 are also visible in the southern Indian, Pacific and Atlantic Oceans. Changes in cloud cover and solar radiation were correlated with broad changes in surface ocean salinity as a result of associated changes in heating of the ocean surface, cloud, and rainfall [*Deser et al*., 2004]. Projections of how cloudiness, solar insolation and precipitation are likely to change as the planet warms have low levels of confidence due to the large interannual variability (ENSO, PDO), short observation time series and uneven spatial sampling, particularly early in the record (before 1950; WG1 2.5.8). Understanding these changes, however, represents a significant knowledge gap and area of future research.

[INSERT FIGURE 30-6 HERE
Figure 30-6: Absolute change over 50 years calculated using regression analysis of data from 1951-2010 (A) Wind Speed as the absolute change in $m.s^{-1}$; (B) Solar radiation as change at the surface of incoming solar insolation in Wm^{-2}; (C) Cloud Cover as the absolute change in total cloud fraction (i.e. If at the beginning of the period the cloud fraction was 0.6 and 0.5 at the end of the period, the change would be -0.1) using NCEP re-analyzed data (www.esrl.noaa.gov); and (D) Salinity as the percentage change from 1960-2010 [reproduced using the data of Durack and Wijffels, 2010]. Data for (A), (B) and (C) were derived from the NCEP/NCAR Reanalysis [*Kanamitsu et al*., 2002]. Monthly mean values for wind speed, total cloud cover and downward solar radiation flux (solar insolation) were obtained from http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.derived.html. At each 1x1 degree grid cell, a linear regression was calculated for each of wind, cloud and solar insolation. The slopes were then multiplied by 600 (months) to calculate the average change over a 50 year period.]

30.3.1.5. Storm Systems

Storm systems range from small atmospheric disturbances to large and violent cyclones, typhoons and hurricanes, and can have both positive and negative influences on ocean ecosystems. As agents of water column mixing, storms can remix nutrients from deeper areas into the photic zone of the ocean, stimulating productivity. Storms can also reduce local sea temperatures and associated stress by remixing heat into the deeper layers of the ocean [*Carrigan and Puotinen*, 2011]. Storms are often highly destructive, however, and can destroy coastal infrastructure and habitats such as coral reefs and mangrove forests which can take decades to recover [*De'ath et al*., 2012].

There is *robust evidence* that the frequency of the most intense cyclones in the Atlantic has increased since 1987 (WG1 2.6.3) and *robust evidence* of inter-decadal changes in the storm track activity within the North Pacific and North Atlantic [*Lee et al*., 2012]. There is also statistically significant evidence of a decrease in tropical cyclones that impacted the East Australian coast is the 19^{th} century, with a significant interaction with long-term variability and land-falling cyclones being twice as common in La Niña versus El Niño years (*high confidence,* [*Callaghan and Power*, 2011]. There has been an increase in the number of intense wintertime extra-tropical cyclone systems since the 1950s in the North Pacific. Similar trends have been reported for the Asian region although analyses are restricted by limitations in terms of the spatial and temporal coverage of reliable records (WG1 2.6.4).

Higher sea temperatures and specific humidities is *likely* to result in fewer yet more intense and damaging storm systems [*Bengtsson et al*., 2009; *Grinsted et al*., 2010]. Wind velocity of tropical cyclones is likely to increase under the influence of warming oceans although the frequency will either decrease or remain unchanged (WGI, 3.4.4). The number of extra-tropical and tropical storm events are *likely* to decrease while average storm intensity is likely to increase [*Bengtsson et al*., 2006; *Bengtsson et al*., 2009; *Landsea et al*., 2010], especially in the Western Atlantic, north of 20°N [*Bender et al*., 2010]. There is *medium confidence* that extra-tropical storm tracks will shift polewards (WGI, 3.4.5). Coastal ecosystems and human communities are likely to experience greater storm surge impacts as increased storm intensity interacts with rising sea levels [SREX 3.5.3, 3.5.5].

30.3.1.6. Thermal Stratification

Greater heat content has resulted in a 4% increase in thermal stratification of the upper layers of the Ocean (0-200 m, 40 year record) except in the case of the Southern Ocean (WG1 3.2.2). Increasing thermal stratification has reduced ocean ventilation and the depth of mixing in most ocean sub-regions (*medium confidence*, 6.3.2, 6.5.2). This in turn reduces the availability of inorganic nutrients and consequently limits primary productivity (*medium confidence*, 6.1.1, 6.2.2.1, 6.2.2.2.3). This has been observed in the STGs which dominate the three major ocean basins (30.5.6), and less so in high-latitude regions where winter convection and deep-water formation are dominant seasonally.

The continued warming of the surface layers of the ocean will *very likely* further enhance stratification and increasingly limit the nutrient supply to euphotic zone. There is *medium evidence* to suggest that the associated loss of primary productivity may be compensated for by enhanced upwelling at high latitudes and from the increasing input of nutrients from coastal systems from human activities (6.1.1.5). The response of upwelling to global warming is *likely* to vary between regions and represents a complex interplay between local and global variables and processes (Box 30-1).

_____ START BOX 30-1 HERE _____

Box 30-1. Upwelling Intensification, Stratification-Ventilation, and Primary Productivity

Bakun [1990] hypothesized that if atmospheric pressure gradients between land and sea expand due to global warming, meridional wind stress that causes upwelling could intensify (Figure 30-16). Empirical support for this hypothesis is equivocal *Bakun* [1990] found supporting trends in some EBUEs, but not others. Similarly, *Narayan et al*. [2010] found mixed results depending on the data sets used. *Garcia-Reyes and Largier* [2010] observed increasing winds and cooling for coastal locations off north-central California (from 36°N to 39°N), but no change to the north or south, while [*Perez et al*., 2010] found that upwelling clearly weakened in the northern Canary Current. Thus trends may vary spatially within systems. Upwelling-favorable winds could lead to increased nutrient input and primary productivity, increasing winds could also result in increased turbulence and offshore advection, factors that may reduce productivity on continental shelves [*Botsford et al*., 2003; *Cury and Roy*, 1989]. In this way, increased upwelling may be associated with increased nutrient input to the euphotic zone, but decreased primary and secondary production.

[INSERT BOX FIGURE HERE
Caption: Diagram illustrating the interaction between land and coastal sea temperature, wind direction and strength, and coastal upwelling.]

More recently, *Rykaczewski and Dunne* [2010] proposed the “stratification-ventilation” hypothesis which hypothesises that climate change could result in enhanced nutrient input and productivity at regional scales. Focusing on the California Current, GCMs were used to show that future increased stratification in the western and central North Pacific could alter the characteristics of waters upwelled in the California Current, with increasing nitrate concentrations being a primary result. The basic argument in this case is that reduced ventilation and mixing of deep, nutrient-rich waters into the euphotic zone over much of the ocean allows continued accumulation of remineralized nutrients in subsurface waters. In sub-regions where these nutrient-enriched waters are forced into the euphotic zone by upwelling processes, nutrient supply and primary production may increase. Thus, primary productivity in the EBUEs may benefit from reduced utilization of nutrients in adjacent, well stratified sub-regions.

_____ END BOX 30-1 HERE _____

30.3.2. Chemical Changes

30.3.2.1. Surface salinity

Ocean salinity varies regionally and is an outcome of the balance between evaporation and the precipitation water from the atmosphere [*Durack and Wijffels*, 2010]; WG1 3.3). Evaporation-dominated regions such as the STGs, Atlantic (except in the Gulf of Mexico and South America; WG1 3.3.3.2) and Western Indian Oceans (Arabian Sea, WG1 3.3.3.1) have elevated salinity, while areas of high precipitation such as the North Pacific, north-eastern Indian Ocean and the eastern Pacific have relatively low salinities (WG1 3.3.3.1 Figure 30-5D). There is *very high confidence* (>99%) that most of these areas have continued to change in the same direction (i.e. a trend of increasing salinity in areas of high salinity and one of decreasing salinity in areas of low salinity (*Durack and Wijffels* [2010], Figure 30-6D).

Salinity trends are strongly consistent with the amplification of the global hydrological cycle [*Durack et al*., 2012; *Pierce et al*., 2012], a consequence of a warmer atmosphere producing greater precipitation, evaporation and extreme events (WG1 3.3.4, Figure 10.14a). These trends are consistent with increases in global temperature, and lead to the conclusion that "it is therefore *likely* that some of the observed changes in surface salinity in the 20th and the early 21st century are attributable to anthropogenic forcing" (WG1 10.4.3, Figure 10.14). Changes in salinity and temperature are consistent with changes expected due to anthropogenic forcing of the climate system and are inconsistent with the effects of natural climate variability, either internal to the climate system (e.g. ENSO, PDO) or external (e.g. solar forcing or volcanic eruptions, [*Pierce et al*., 2012]. There are *high agreement* between CMIP3 climate models that these trends in ocean salinity are expected to continue as average global temperature [*Terray et al*., 2012]. Ramifications of these changes are largely uncertain but are of great interest given the role of ocean salinity and temperature in fundamental processes such as the AMOC.

30.3.2.2. Ocean Acidification

Increased atmospheric CO_2 from human activities has increased the flux of CO_2 into the Ocean, resulting in decreased ocean pH as well as carbonate and bicarbonate ion concentrations (Box CC-OA). The extent to which the added influx of CO_2 into the Ocean has acidified and influenced the tendency for aragonite or calcite (polymorphs of calcium carbonate) to precipitate into the shells and skeletons of marine organisms depends mostly on the solubility of CO_2 and calcium carbonate, both of which decrease as temperature increases or depth decreases. Other factors such as atmosphere-ocean heat exchange, ocean circulation, and land-sea interactions (WG1 6.4) play significant roles in determining the saturation state of seawater for the polymorphs of calcium carbonate. Consequently, pH and the saturation states of aragonite and calcite are naturally lower at high latitudes and in upwelling areas (e.g. Eastern Pacific upwelling, Californian Current) which may be relatively more vulnerable to ocean acidification as a result [*Gruber et al*., 2012](Figure 30-7 A, B). These two variables also decline with depth, calcite reaching its saturation horizon between 3,000 and 4,500 m, and aragonite reaching its saturation horizon between 1000 m and 2500 m in the Pacific and Atlantic oceans respectively [*Orr et al*., 2005].

Surface ocean pH has declined by approximately 0.1 pH units since the beginning of the Industrial Revolution (*very high confidence*, WG1, 3.8.2, Box 3.2) with significant shoaling of the saturation horizons of both polymorphs of calcium carbonate [*Orr et al*., 2005]. Oceanographic studies have measured the ongoing decline in ocean pH (–0.0015 and –0.0024 pH units per year; WGI 3.8.2, Figure 3.17) and the saturation state of calcium carbonate polymorphs (WG1 Figure 3.17). These changes can be strongly attributed to the increase in anthropogenic CO_2 emissions to the atmosphere (*very high confidence*, WGI 3.8.2, Box 3.2 and Table 10.1) and are at least 10 times faster than accumulation of atmospheric CO_2 than during the Paleocene-Eocene Thermal Maximum (PETM; 6.1.2, *high confidence*). The impacts of ocean acidification on marine organisms and ecosystems has emerged as a major concern especially given the *robust evidence* that the current chemistry of the ocean is outside where it has been for million years [*Pelejero et al.*, 2010; *Zeebe*, 2012]. At current rates of atmospheric CO_2 increase, changes to the chemistry of the ocean will surpass any seen over the last 40 million years [*Hoegh-Guldberg et al.*, 2007; *Raven et al.*, 2005; *Tyrrell and Zeebe*, 2004] and possibly 300 million years (6.1.2).

Observations from a wide range of laboratory, mesocosm, and field studies reveal that marine organisms and ocean processes are sensitive to levels of ocean acidification projected under elevated atmospheric CO_2 (Box CC-OA, 6.2.2, 6.3.4, [*Kroeker et al.*, 2013], *high confidence*). Ecosystems that are characterised by high rates of calcium carbonate deposition (e.g. coral reefs, plankton communities) are sensitive to decreases in the saturation states of aragonite and calcite (*high confidence*). These changes are *very likely* to have broad consequences such as the loss of three-dimensional coral reef frameworks [*Dove et al.*, 2013; *Hoegh-Guldberg et al.*, 2007] and restructuring of food webs at relatively low concentrations of atmospheric CO_2. Similarly, organisms sensitive to changes in pH with respect to physiological processes such as respiration and neural function are also expected to respond to the rapid changes in pH and ocean chemistry (6.3.4). Due to the relative short history of ocean acidification studies, and the current expanding effort to understand this problem, there are a growing number of organisms and the processes that are being identified as sensitive to the influence of anthropogenic changes to ocean chemistry.

Projected changes to the atmospheric CO_2 will further acidify the ocean and change its chemistry (Figure 30-7; WG1 Figure 6.28). Doubling CO_2 will decrease ocean pH by another 0.1 pH units and decrease carbonate ion concentrations by approximately 100 mmol kg^{-1} (from an average of 250 mmol kg^{-1}; *high confidence, Orr et al. [2005]*)(WG1 6.4, Figure 6.28). The saturation horizons will also become significantly shallower in all oceans, with the aragonite saturation horizon line between 0 and 1500 m in the Atlantic and, 0 and 600 m (poles versus equator) in the Pacific Ocean [*Orr et al.*, 2005] WG1 6.4, Figure 6.28). Trends towards under-saturation of aragonite and calcite will also depend on ocean temperature, with polar waters expected to be undersaturated with respect to aragonite and calcite within a couple of decades (Box CC-OA; 6.4.4). These changes will also be accompanied by a shoaling of the aragonite and calcite saturation horizons that is *very likely* to have serious ramifications for deep water communities such as deep water scleractinian corals and other benthic organisms [*Guinotte et al.*, 2006].

[INSERT FIGURE 30-7 HERE
Figure 30-7: A. Surface pH and B. aragonite saturation state of the Ocean at different atmospheric CO_2 levels simulated by the University of Victoria Earth System Model. The fields of pH and aragonite saturation state are calculated from the model output of dissolved inorganic carbon concentration, alkalinity concentration, temperature, and salinity, together with the chemistry routine from the OCMIP-3 project (http://www.ipsl.jussieu.fr/OCMIP/phase3).]

30.3.2.3. Oxygen Concentration

Dissolved oxygen is a major determinant of the distribution and abundance of marine organisms (6.2.2.1.). Oxygen concentrations vary across the ocean basins, tending to be lower in the eastern Pacific and Atlantic basins, and northern Indian Ocean (Figure 30-8; 6.1.1.3). By contrast, some of the highest concentrations of oxygen are associated with cooler high latitude waters (WG1 Figure 3.19). Long-term records of oxygen concentrations in ocean waters are rare. However, there is high agreement that open ocean oxygen concentrations in the thermocline have declined by 0.09 to 0.34 μmol kg^{-1} $year^{-1}$ since 1960 and it is *very likely* that the tropical oxygen minimum zones have expanded over recent decades (WG1 3.8.3; *Stramma et al.* [2008]). These changes are consistent with the solubility of oxygen declining with higher temperatures and with increased water column stratification reducing ocean-atmosphere ventilation. Analysis of ocean O_2 trends over time [*Helm et al.*, 2011a] reveals that the basic phenomenon of O_2 solubility decreasing with increased temperature is responsible for no more than 15% of the observed change. The remaining 85%, consequently, must be attributed to increased deep-sea microbial respiration and reduced O_2 supply from increased ocean stratification (WG1 Box 6.5 Figure 1). Eutrophication of coastal areas, for example, can lead to increased transport of organic carbon into ocean habitats where microbial metabolism is stimulated resulting in a rapid drawdown of oxygen [*Bakun et al.*, 2010; *Rabalais et al.*, 2009; *Weeks et al.*, 2002].

It is *likely* (*limited evidence, medium agreement*) that areas of low O_2 concentrations in deep water are expanding in many parts of the world (WGI 3.8.3) with impacts on marine life including mass mortality and the subsequent exclusion of fish and other metazoans from expanding "dead zones" (*high confidence*, [*Diaz and Rosenberg*, 2008](6.2.2, 6.3.3). These areas are rapidly expanding due to regional human drivers not directly related to climate change (i.e. eutrophication of coastal areas) in addition to drivers that are (e.g. increasing sea temperature, increasing stratification, changes in terrestrial run-off and reduced ventilation from changing wind stress). Climate change at a decadal time scales is also driving the widespread increase in hypoxia through the reduction in oxygen concentrations arising due to reduced solubility, temperature effects on microbial respiration, and increased water column stratification. The subarctic Pacific is perhaps the best example of an ocean basin where physical forcings are clear, where Siberian warming leads to reduced ice formation, a reduction in dense water formation and a weakening oxygen transport into the interior ocean [*Nakanowatari et al.*, 2007].

The development of hypoxic conditions (generally defined as O_2 concentrations below 60 μmoles kg^{-1}) over recent decades has been documented across a wide array of ocean sub-regions including SES (Black and Baltic Seas), the Arabian Gulf, and the California, Humboldt and Benguela current systems (Figure 30-8), where eruptions of hypoxic, sulfide-laden water have occurred [*Weeks et al.*, 2002]. Localized seasonal hypoxic zones have emerged in economically valuable coastal areas such as the Gulf of Mexico [*Rabalais et al.*, 2010; *Turner et al.*, 2008], the Baltic Sea [*Conley et al.*, 2009] and Black Sea [*Kideys*, 2002; *Ukrainskii and Popov*, 2009], in connection with nutrient fluxes from land. Over a vast region of the Eastern Pacific stretching from southern Chile to the Aleutian Islands, the minimum pO_2 threshold (< 2 mg.l^{-1} or 60 mmol kg^{-1}) is found at only 300-m depth and upwelling of increasingly hypoxic waters is well documented [*Grantham et al.*, 2004]. Hypoxic waters in the northern Arabian Sea and Bay of Bengal are located close to continental shelf depths. Long-term measurements are revealing that oxygen concentrations are declining in these waters, with *medium evidence* that economically significant mesopelagic fish populations are being threatened [*Koslow et al.*, 2011]. The Atlantic Ocean differs from the Pacific and Indian Ocean as hypoxic conditions in this respect are largely limited to the regions at and adjacent to the two EBUE due to its better ventilation. The calculation of hypoxia profiles according to an assumed critical threshold of 60 mmol kg^{-1} are illustrative although this can convey an overly simplistic message given that critical concentrations of O_2 are species and life history stage specific, showing a great dependence on body size and/or temperature. This variability in sensitivity is critical to how ecosystems are likely to respond to this aspect of climate change (6.3.3).

It is *very likely* that further increases in ocean temperature will lead to decreased oxygen concentrations due to the effect of temperature on O_2 solubility and water column stability (reduced ocean ventilation). There is *high agreement* among modelling studies that the total oxygen within the ocean will decline under future scenarios (WG1 Table 6.14). The outcomes of these global changes will be influenced by regional differences in wind stress, coastal processes, and the production and consumption of organic matter by microbes.

[INSERT FIGURE 30-8 HERE
Figure 30-8: Map of the depth [*Hofmann et al.*, 2011] at which a critical value of partial pressure of O_2 of 60 matm occurs which is widely accepted as threatening to marine life on continental shelves (200m depth). Conventional maps of oceanic oxygen values report simple mass properties with no temperature or depth dependence; a better rendition of the availability of O_2 to marine life is provided by the partial pressure, which includes the temperature terms. Critical sub-regions in the eastern and northern Pacific and in the northern Indian ocean stand out. In these areas quite modest upward expansion of the depth at which the critical pO_2 level occurs can have negative effects on major fish populations. Note: not all areas have been included – for example, significant hypoxia in the Gulf of Mexico is not been shown.]

30.4. Global Responses by Marine Organisms to Climate Change (including Ocean Acidification)

There has been a rapid increase in studies that focus on climate change impacts on marine ecosystems since AR4 ([*Hoegh-Guldberg and Bruno*, 2010; *Poloczanska et al.*, 2013] representing an opportunity to examine and potentially attribute detected changes within the Ocean to climate change. *Poloczanska et al*. [2013] applied the 'vote-counting' approach used by *Parmesan and Yohe* [2003]; *Root et al*. [2003] and *Rosenzweig et al*. [2008] to show a coherent pattern in responses of ocean life to recent climate change across regions and taxonomic groups using a global database of observed responses (1735 responses in 857 species or assemblages from 208 peer-reviewed papers). (Figure 30-9; [*Poloczanska et al*., 2013]. Observations were defined as those where the authors of a particular paper assessed the consistency of change in a biological parameter (namely distribution, phenology, abundance, calcification, demography or community composition) with climate change. Studies from the peer-reviewed literature were selected using three criteria: (1) authors inferred or directly tested for trends in biological and climatic variables; (2) data after 1990 were included; and (3) observations spanned at least 19 years, to minimize bias resulting from short-term biological responses to natural climate variability. Approximately 90% of the studies identified temperature as the primary driver of change, with the remainder focusing on sea ice, pH and climate oscillation, where changes have been explicitly linked to global warming.

[INSERT FIGURE 30-9 HERE
Figure 30-9: (A) 1735 observed responses to climate change from 208 single- and multi-species studies showing responses that are consistent with climate change (blue), opposite to expected (red) and are equivocal (yellow). Each circle represents the centre of a study area. Where points fall on land, it is because they are centroids of distribution that surround an island or peninsula. Pie charts show the proportions within regions bounded by red squares and in the Mediterranean; numbers indicate the total (consistent, opposite plus equivocal) observations within each region. (B) Frequency of observations by latitude. (C) South-west Pacific. (D) North-east Atlantic. (E) California Current. (F) North-west Pacific (Poloczanska et al 2013).]

The results of this meta-analysis suggest that climate change is having an impact on species in many different ways across a broad range of taxonomic groups (plankton to top predators). Of the observations that showed a response in either direction, 84% were in a direction that was consistent with climate change (Fig. 30-10). For these, consistency was variable according to taxonomic group (Figure 30-10A), latitudinal band (Figure 30-10B), and biological response parameter (Figure 30-10C). Despite remaining knowledge gaps, especially in equatorial sub-regions and the Southern Hemisphere, it is clear that recent climate change has already had widespread impacts on marine organisms and ecosystems.

[INSERT FIGURE 30-10 HERE
Figure 30-10: Percent of responses consistent with climate change predictions. Mean and standard error of responses by (A) taxa, (B) latitudinal region and (C) response measure show significantly higher consistency than expected from random (dashed line at 50% consistency). Solid line is the mean across all observations. Significance of results is listed next to labels (***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$). Sample sizes are listed to the right of each row.]

The overall mean (± SE) rate of re-distribution for marine biota was 72.0 ± 13.5 km decade^{-1} measured at leading range edges and 15.8 ± 8.7 km decade^{-1} at trailing edges, with most of the data collected from 1950 onwards (Figure 30-10B) revealing much higher rates of migration than reported for terrestrial species. The average rate of change on land was 6.1 ± 2.4 km decade^{-1} when calculated across taxa [*Parmesan and Yohe*, 2003] or 19.7 ± 3.7 km decade^{-1} calculated across regional taxonomic groupings [*Chen et al*., 2011]. Similarly, spring timing showed advances of -4.4 ± 0.7 day.decade^{-1} in marine systems (Figure 30-11A [*Poloczanska et al*., 2013]), contrasting with -2.8 ± 0.35 day.decade^{-1} for terrestrial species [*Parmesan*, 2007]. Similar trends are seen for the delayed arrival of fall/winter in both hemispheres.

[INSERT FIGURE 30-11 HERE
Figure 30-11: Rates of change in (A) phenology (days.decade^{-1}) measured during spring (red) and summer (brown); and (B) distribution (km.decade^{-1}) for marine taxonomic groups, measured at the leading edges (red), and trailing edges (brown). O (brown). Average distribution shifts calculated using all data, regardless of range location, are in black. Distribution rates have been square-root transformed; standard errors may be asymmetric as a result. Positive distribution changes are consistent with warming (into previously cooler waters, generally poleward) and negative phenological changes are consistent with warming (generally earlier). Means ± standard error are shown, with number of observations and significance (*$p<0.1$, **$p<0.05$, ***$p<0.01$); Poloczanska et al, 2013).]

The faster expansion rates of leading edges compared to contraction of trailing edges can be partly explained by the speed and direction at which isotherms propagate across the Ocean's surface [*Burrows et al*., 2011; *Loarie et al*., 2009] in study regions. Both the leading and trailing range edges for ectothermic marine organisms are likely to be equally responsive to warming temperatures [*Sunday et al*., 2012]. The velocity of isotherm migration in the ocean over 1960-2009 [*Burrows et al*., 2011] varies considerably, with locally fast and slow sub-regions. Rapid velocities (>50 km.decade^{-1}) were observed in the North Sea, the sub-Arctic Pacific and Atlantic, and within 15° of the equator, implying a risk of large ecological responses (Figure 30-3B, [*Burrows et al*., 2011]). Rates of climate change, such as climate velocity, over longer time periods can help to explain both present-day distribution patterns and shifts in biodiversity [*Sandel et al*., 2011].

Poloczanska et al. [2013] reveal that climate change is resulting in changes to organisms and ecosystems within the world's oceans (*robust evidence, high agreement,* and *high confidence*). Diagnostic fingerprints, uniquely predicted by twentieth century climate trends, provide convincing evidence that climate is the primary driving force behind the observed biological changes, strengthening the attribution of detected changes to climate change (Parmesan and Yohe 2003). These include concurrent increases of 'warm-water' species and decreases of 'cool-water' species, as expected with climate change, within regions. Consistent responses were recorded across multiple poleward or equatorward edges of distributions that were widely separated (such as for fish populations in north-west Atlantic and north-east Atlantic, and discussed in regional assessments below).

30.5. Regional Impacts, Risks, and Vulnerabilities: Present and Future

This section explores the impacts, risks and vulnerabilities of climate change for the seven sub-regions within the Ocean. There is considerable variability from region to region, especially in the extent and interaction of climate change and non-climate change stressors. While the latter may complicate attribution attempts in many sub-regions, interactions between the two types of stresses may also represent opportunities to reduce the overall impact on marine organisms and processes by environmental changes being driven by climate change (including ocean acidification).

30.5.1. High-Latitude Spring Bloom Systems

High-latitude Spring Bloom Systems (HLSBS) stretch from 35º N and S to the edge of the winter sea ice and provide 36% of world's fishery catch (Table 30-1, Figure 30-1). Strong seasonal cycles of primary productivity are pronounced at high latitudes, which create phytoplankton spring-bloom dynamics, and follow the latitudinal gradient in light intensity [*Racault et al*., 2012]. Efficient transfer of marine primary and secondary production to higher trophic levels, including commercial fish species, is influenced by the magnitude and spatial and temporal synchrony between successive trophic production peaks [*Beaugrand and Reid*, 2003; *Beaugrand et al*., 2003; *Cushing*, 1990; *Hjort*, 1914].

30.5.1.1. Observed Changes and Potential Impacts

30.5.1.1.1. North Atlantic

The North Atlantic is one of the most intensively fished ocean sub-regions. The major areas for harvesting marine living resources span the eastern American, European and Icelandic shelves [*Livingston and Tjelmeland*, 2000]. In addition, the Deep Sea regions of the Nordic Seas and the Irminger Sea contain large resources of pelagic and mesopelagic fish such as herring, blue whiting, mackerel and redfish. The region covers a wide latitudinal range from 35º to 80ºN, and, hence, a large span in thermal habitats. This is reflected in the latitudinal gradients from subtropical/temperate species along the southern fringe to boreal/arctic species along the northern fringe.

The North Atlantic HLSBS shows prominent and robust warming trend resulting in an increase in temperature of 3.97ºC from 1955 to 2005 (Table 30-2). Since the 1970s, the Atlantic Ocean has warmed more than any other Ocean basin (0.3ºC decade^{-1}; Table 30-2; WGI Chapter 3) with greatest warming rates over European continental shelf areas such as the southern North Sea, the Gulf Stream front, the sub-polar gyres and the Labrador Sea [*González-Taboada and Anadón*, 2012; *Lee et al*., 2011; *Levitus et al*., 2009; *Mackenzie and Schiedek*, 2007a; b]. Nearly half of the basin-wide warming in the North Atlantic since the mid-1990s has been driven by global warming, with the rest being contributed by the Atlantic Multi-decadal Oscillation [*Wang and Dong*, 2010].

Observations and modeling indicate increased primary production with increasing temperature [*Mueter et al*., 2009; *Steinacher et al*., 2010], and poleward displacement of species [*Cheung et al*., 2011; *Stenevik and Sundby*, 2007]. The subsequent examples, mainly from the Barents, Nordic, and North Seas how warming from the early 1980s has influenced North Atlantic ecosystems where substantial biological impacts have been observed including large-scale modification of the phenology, abundance and distribution of plankton assemblages and reorganization of fish assemblages [*Beaugrand et al*., 2002; *Edwards*, 2004; *Edwards and Richardson*, 2004; *Nye et al*., 2009; *Simpson et al*., 2011; *Tasker*, 2008] Changes are also evident towards the southern fringe of North Atlantic HLSBS where southern species of molluscs and fish have expanded into the Bay of Biscay [*Bañón et al*., 2010; *Guerra et al*., 2002] and juvenile Bluefin Tuna (*Thunnus thynnus*) and Albacore Tuna (*Thunnus alalunga*) on summer feeding migrations are arriving earlier from 1967-2005 due to warming and subsequent shifts in prey assemblages [*Dufour et al*., 2010].

The past decade has been the warmest decade ever recorded in the Barents Sea resulting in large populations of krill, shrimp, pelagic and demersal fish stocks linked to the Atlantic and boreal ecosystem of the Barents Sea [*Johannesen et al*., 2012]. The relatively warm Atlantic waters have advanced northward and eastward [*Årthun et al*., 2012] and sea-ice has retreated along with the Arctic water masses. As a result, boreal euphausiids, which are mainly confined to the Atlantic water, have increased in biomass and distribution [*Dalpadado et al*., 2012] enhancing growth of young cod *Gadus morhua* (boreal) as well as the more Arctic (arcto-boreal) capelin (*Mallotus villosus*). The amphipods of more Arctic origin have decreased, resulting in poorer feeding conditions for polar zooplankton predators such as polar cod (*Boreogadus saida*). Blue whiting (*Micromesistius poutassou*) which spawn west of the British Isles, feed on zooplankton in the Norwegian Sea during the summer. During the recent warming period, the summer feeding distribution of the whiting extended into the Barents Sea. In summary, the long-term trend of pelagic fish species has increased in the Barents Sea, although with pronounced decadal-scale oscillations superimposed over long-term climate trends. The recruitment to boreal fish stocks like cod, haddock, and herring has increased in the Barents Sea [*Eriksen et al*., 2012]. Climate change by 2100 is *virtually certainly going* to impact the northern fringes of the Atlantic HLSBS with increases in zooplankton production of 20 % in the Barents Sea [*Ellingsen et al*., 2008] as temperatures increase and Atlantic species replace the Arctic ones (*medium evidence, high agreement,* and *high confidence*). Together with poleward shifts of fish species, a substantial increase in fish biomass and catch is also *very likely* [*Cheung et al*., 2011]. However, the continuous temperature increase is *very likely* to cause discontinuous changes in life cycle conditions for some species like the capelin which feeds in summer at the ice edge and spawns in spring at the southern Atlantic Norwegian/Murman coast of the Barents Sea. The limited migration potential for this small pelagic fish is *likely* to cause it to switch spawning areas to the similar, but far separated spawning grounds at the Novaja Semlja coast with the only alternative to go extinct [*Huse and Ellingsen*, 2008].

The Norwegian Sea is one of the two core regions for the herbivore copepod *Calanus finmarchicus* that is an important prey species for pelagic fish and early life-stages of all fish around the rim including the North Sea and the Barents Sea [*Sundby*, 2000]. *C. finmarchicus* is the main food item for some of the world's largest fish stocks such as the Norwegian spring-spawning herring (*Clupea harengus*), blue whiting (*M. poutassou*) and Northeast Atlantic mackerel (*Scomber scombrus*). These stocks have increased considerably during the recent warming from the early 1980s [*Huse et al*., 2012]. Also, the individual size of herring has increased enabling longer feeding migration routes to utilize zooplankton closer to more distant Arctic water masses towards northwest. Mackerel has advanced northward and westward into Icelandic waters [*Astthorsson et al*., 2012]. Since 2008, however, biomass of the pelagic fishes has decreased along with a decreasing biomass of the *C. finmarchicus*, indicating a switch in the system to a top-down control. This demonstrates that even though fish stocks are expected to increase in high latitude regions under climate change this increase is limited by the productivity in zooplankton.

There is *high confidence* that observed changes in the phenology of plankton groups in the North Sea is being driven by regional warming [*Edwards and Richardson*, 2004; *Lindley and Kirby*, 2010; *Lindley et al.*, 2010; *Schluter et al.*, 2010; *Wiltshire and Manly*, 2004; *Wiltshire et al.*, 2008]. Phenological responses of zooplankton were species-specific with substantial variation within functional groups. For example, the peak maximum abundance of the copepod *Calanus finmarchicus* advanced by 10 days from the 1960s to the 2000s, but it's warm-water equivalent, *C. helgolandicus,* did not advance [*Bonnet et al.*, 2005]. The appearance of larvae of benthic fauna in the meroplankton corresponds to the timing of adult reproductive cycles, so shifts in adult phenology [*Beukema and Dekker*, 2005; *Philippart et al.*, 2003] have implications for biological linkages between benthic and pelagic ecosystems [*Kirby et al.*, 2007; *Lindley et al.*, 2010]. The ranges of some cold-water zooplankton assemblages in the North-east Atlantic have contracted towards the Arctic since 1958, and many warm-water zooplankton assemblages (specifically copepods) have replaced them (*high confidence*), moving up to 1000 km northward [*Beaugrand*, 2009; *Beaugrand et al.*, 2002].

Fish communities from both the North-west and North-east Atlantic show distributional shifts (*high confidence*) although the direction of these changes varies among species. Fish communities are also shifting to greater depths due to warming [*Dulvy et al.*, 2008; *Nye et al.*, 2009; *Perry et al.*, 2005; *Tasker*, 2008]. In the North Sea, bottom temperatures in winter have warmed by 1.6°C (1980- 2004, [*Dulvy et al.*, 2008]. The whole demersal fish community shifted deeper by 3.6 m decade^{-1} over the period 1980-2004, although mean latitude of the whole community did not show net displacement [*Dulvy et al.*, 2008]. Within the community, cool-water specialists generally shifted northwards while abundant warm-water species shifted southwards reflecting winter warming of the southern North Sea. The cold winter temperatures of the shallow regions of the southern North Sea have acted to exclude species with warm-water affinities. Trawl survey data from the rapidly-warming southern North Sea suggests waves of immigration by southern species, such as red mullet (*Mullus surmuletus*), anchovy (*Engraulis encrasicholus*) and sardines (*Sardina pilchardus*), linked to increasing population sizes and warming temperatures [*Beare et al.*, 2005]. In the high-latitude North Atlantic diversity of zooplankton and fish has increased, as more diverse warm-water assemblages extend northward in response to changing environmental conditions [*Beaugrand*, 2009; *Hiddink and ter Hofstede*, 2008; *Kane*, 2007; *Mountain and Kane*, 2010; *ter Hofstede et al.*, 2010]. Southern (warm-water) species of fish have increased in abundance on both sides of the North Atlantic (*medium confidence*) [*Beare et al.*, 2005; *Collie et al.*, 2008; *Hermant et al.*, 2010; *Lucey and Nye*, 2010; *Simpson et al.*, 2011].

Range expansions and contractions linked to changing climate have also been found in benthic crustaceans, bivalves, gastropods, and polychaetes [*Berke et al.*, 2010; *Beukema et al.*, 2009; *Mieszkowska et al.*, 2007]. For example, the southern range of the common intertidal barnacle *Semibalanus balanoides* in the North-east Atlantic has been contracting at a rate of 15-50 km decade^{-1} since 1872, and the retreat is attributed to reproductive failure as winter temperatures warm [*Southward et al.*, 2005; *Wethey and Woodin*, 2008]. The warm-water competitor *Chthamalus montagui* of *S. balanoides* has increased in abundance to replace the niche vacated by *S. balanoides* [*Poloczanska et al.*, 2008; *Southward et al.*, 1995]. Changes in the distribution of seaweed species have been observed along the coastline of the Iberian Peninsula where a latitudinal gradient in temperature is observed all year despite summer upwelling. In particular, some large seaweeds with a cold-water affinity have contracted their distribution limits [*Díez et al.*, 2012; *Fernández*, 2011; *Lamela-Silvarrey et al.*, 2012] while species with a warm-water affiliation have expanded [*Lima et al.*, 2007].

Most of the longest and most comprehensive time series used to investigate the ecological consequences of climate fluctuations and fishing are from this region [*Edwards et al.*, 2010; *Poloczanska et al.*, 2013; *Southward et al.*, 2005; *Sundby and Nakken*, 2008; *Toresen and Østvedt*, 2000]. Meta-analysis of 288 long-term datasets of zooplankton, benthic invertebrates, fish and seabirds from the OSPAR Commission Maritime Area in the north east Atlantic showed wide-spread changes in distribution, abundance and seasonality that were consistent (75%) with expectations from enhanced greenhouse warming [*Tasker*, 2008]. The study bought together evidence of changes in ocean climate, and ecological responses across a range of species that encompassed both exploited and unexploited species from a variety of information types including peer-reviewed reports from ICES Working Groups [*Tasker*, 2008]. In particular, observations showed polewards shifts in zooplankton communities, increasing abundance of fish species in the northern part of their ranges and decreases in southern parts, and the expansion of benthic species into more northerly or less coastal areas.

The major part of the literature on climate impacts for the North Atlantic region covers time spans longer than for most other sub-regions of the Oceans. Even here, however, most of the literature is limited to the recent 30 to 50 years. The few publications covering the first half of the 20th century represent an important longer-term perspective to the impacts of climate change [*Astthorsson et al.*, 2012; *Bañón*, 2009; *Drinkwater*, 2006; *Sundby and Nakken*, 2008; *Toresen and Østvedt*, 2000]. For example, distinct changes in fauna were associated with a pronounced warming period of 1920-1940 [*Wood and Overland*, 2010] when fish and other fauna moved northward [*Drinkwater*, 2006; *Hátún et al.*, 2009; *Iversen*, 1934; *Southward et al.*, 1995]. The major lesson from these reports is that an almost similar large-scaled temperature increases occurred in the high-latitude North Atlantic from 1910s to the 1940s as that which occurred during the last 30 years, with similar basin-scale impacts on marine ecosystems. The former event was of great concern within the scientific community, particularly during the late 1940s and early 1950s [*Iversen*, 1934; *Tåning*, 1949; *Tåning*, 1953]. With the subsequent long-term cooling in the 1970s, however, discussion around climate impacts has unfortunately discontinued. The present centennial-long perspectives indicate that the major fraction of the impacts from the recent 30-year temperature increase is part of multidecadal changes with the crucial message that understanding the scenarios for the anthropogenic climate change over the next century is particularly important. We are only beginning to see the early contours of this development. Under the assumption that the long-term natural climate variability continues through 21st century with the same frequency and amplitude as during the 20th century we could expect that we have already reached a culmination of the multidecadal signal with only limited temperature increase over the next 20 years until again the anthropogenic and natural climate signal are adding up in the same direction. Under such a scenario, the climate of the North Atlantic climate is projected to change more rapidly around 2050 than ever recorded (*high confidence*).

30.5.1.1.2. North Pacific

Sub-decadal variability in the North Pacific HLSBS is dominated by ENSO [*Trenberth*, 1990], WGI Chapter 14). Like the North Atlantic HLSBS, the North Pacific HLSBS has shown high rates of warming, with an increase in average sea temperature of 4.62°C from 1955 to 2005 (based on data from 1950 to 2009, Table 30-2). Decadal and longer periods of variability in the North Pacific are reflected in two principal modes; the Pacific Decadal Oscillation (PDO) with periodicities at both 15-25 y and 50-70 y in SST [*Mantua and Hare*, 2002; *Minobe*, 1997], and the Victoria Pattern [*Bond et al.*, 2003] and the North Pacific Gyre Oscillation (NPGO). The PDO exhibits SST anomalies of one sign along the eastern boundary and the opposite sign in western and central Pacific (WGI 14.6.6), The PDO has been reported to have an anthropogenic component thus confounding statistical approaches aimed at removing natural variability from ecological time-series [*Bonfils and Santer*, 2011]. The interplay of the phases of these modes of variability has strong influence on high-latitude Pacific ecosystems. In the space of three years, the eastern North Pacific fluctuated from one of the warmest years in the past century (2005) to one of the coldest (2008) [*McKinnell and Dagg*, 2010; *McKinnell et al.*, 2010]. This rapid change was accompanied by large changes in primary productivity, zooplankton communities and fish and seabirds [*Batten and Walne*, 2011; *Bi et al.*, 2011; *Keister et al.*, 2011; *McKinnell and Dagg*, 2010; *McKinnell et al.*, 2010].

Periods of broad-scale environmental regime shifts are observed across high-latitude ecosystems in the North Pacific (eastern Bering Sea and Gulf of Alaska) during 1976-78, 1987-89 and 1998-99. These periods were associated with regime shifts in forage fish that occurred in 1979-82, 1988-92 and 1998-2001. These changes indicate of how basin-scale variability such as PDO can manifest across distinct ecosystems [*Link et al.*, 2009a; *Link et al.*, 2009b; *Overland et al.*, 2008]. Climate regime shifts are characterized by abrupt reorganization of the ecosystems as dynamic trophic relationships among species alter [*Alheit*, 2009; *Hunt et al.*, 2002; *Litzow and Ciannelli*, 2007; *Litzow et al.*, 2008]. Phenological shifts have been observed in the zooplankton communities of the North Pacific in response to decadal climate cycles with distinct changes noted after the climate regime shifts of the 1970s and 1990s [*Chiba et al.*, 2006; *Mackas et al.*, 1998]. In the North-west Pacific, springtime copepod abundance also increased linearly over the period 1960-2002 [*Chiba et al.*, 2006]. Regime shifts in the mid-1970s and late-1980s were also reported in the Kuroshio-Oyashio Extension (KOE) in the North-west Pacific with dramatic changes in pelagic ecosystems and sardine and anchovy stocks [*Chiba et al.*, 2008; *Yatsu et al.*, 2008]. Climate change model simulations show global warming could further alter the dynamics of the Kuroshio Current and the Kuroshio Extension dynamics over the coming century [*Sakamoto et al.*, 2005] that will alter timing, magnitude and structure of spring-blooms in the western Pacific with implications for pelagic fish production and biogeochemical cycles [*Hashioka et al*., 2009].

Commercial catches of salmon species in the North Pacific follow decadal climate changes [*Hare and Mantua*, 2000; *Mantua and Hare*, 2002]. Catches peaked in the warm periods of the 1930s-1940s and 1990s-2000s with 2009 yielding the highest to date, and warming trends may have contributed to recent peak in some sub-regions [*Irvine and Fukuwaka*, 2011; *Morita et al*., 2006]. Anticipating ecological responses to future anthropogenic climate change also requires evaluation of the role changes to climate beyond warming *per se*. For example, declining sea level pressure (SLP) in the North Pacific is anthropogenically forced [*Gillett et al*., 2003], and SLP in turn is related to atmospheric climate parameters (e.g., turbulent mixing via wind stress) that regulate commercially significant fish populations [*Wilderbuer et al*., 2002].

The Bering Sea region is among the most productive of marine sub-regions, and includes the world's largest single-species fishery which fishes for walleye Pollock *Theragra chalcogramma* [*Hunt et al*., 2010]. This region has undergone major changes in recent decades as a result of climate variability, climate change and fishing impacts [*Hunt et al*., 2010; *Jin et al*., 2009; *Litzow et al*., 2008; *Mueter and Litzow*, 2008]. SSTs have increased at a rate of 0.23°C.decade^{-1} over 1982-2006 [*Mueter and Litzow*, 2008] but since 2006 it has been colder than the long-term average [*Coyle et al*., 2011]. Seasonal sea ice cover strongly influences the Bering Sea ecosystem through regulating the spring bloom and extent of the "cold pool" ; an area of reduced water temperature <2°C on the northern Bering Sea shelf that is formed as a consequence of sea ice and is maintained over summer [*Hunt et al*., 2010]. Seasonal sea ice has declined since the 1990s (to 2006), although there is no linear trend 1953-2006, and the initiation of spring ice retreat over the south-eastern Bering Sea shelf occurred earlier [*Wang et al*., 2007a; *Wang et al*., 2007b]. Concurrent with a retreat of the cold pool, bottom trawl surveys of fish and invertebrates show a significant community-wide northward distribution shift and a colonization of the former cold pool areas by subarctic fauna [*Mueter and Litzow*, 2008; *Wang et al*., 2006a]. Total biomass (mean catch per unit effort) has increased dramatically in the northern survey area, including the area around the Pribilof Islands [*Mueter and Litzow*, 2008]. The shallow waters of the eastern Pacific Ocean are low in oxygen (Figure 30-8). Coastal upwelling along the continental shelf can cause mortality of coastal fishes and invertebrates [*Grantham et al*., 2004], whereas decreasing oxygen concentrations at depth in the subtropics are explained by changes in the gyre circulation in response to 20th century climate change. The role of climate change in decreasing the oxygen concentration at higher latitudes remains unclear although changes in ocean mixing and ventilation are likely to be contributing factors [*Deutsch*, 2005].

30.5.1.1.3. Southern Hemisphere

The seasonal peaks in phytoplankton productivity in the southern hemisphere are much less pronounced and of smaller magnitude as those in northern hemisphere high-latitudes [*Yoder et al*., 1993]. The southern hemisphere HLSBS is broadly bounded by the sub-tropical front (STF) and sub-Antarctic front. Associated with the STF is intense biological activity by bloom-forming coccolithophores (phytoplankton) [*Brown and Yoder*, 1994]. The calcifying plankton assemblages play a key role in carbon cycles in the region and the transport of carbon to deep ocean sediments. The coccolithophore *Emiliania huxleyi* has extended its range south of 60° in the south-west Pacific (141-145°E) over the two decades since 1983 [*Cubillos et al*., 2007]. Although the drivers for this range extension are not clear, it is proposed that the extension is facilitated by surface warming or changes in the abundance of grazing zooplankton.

While the South Pacific HLSBS has not shown warming overall (1950 to 2009, Table 30-2), some areas within the HLSBS have warmed very significantly. There is *high confidence*, for example, that the western Tasman Sea has shown enhanced warming since 1900 as compared to average global trends. This has been driven by changes in large-scale wind-forcing leading to a southward expansion of the South Pacific STG and intensifying the southward-flowing East Australian Current (EAC) [*Cai*, 2006; *Hill et al*., 2008; *Wu et al*., 2012]. Model simulations suggest both stratospheric ozone depletion and greenhouse forcing contribute equally to the observed trend in wind stress [*Cai and Cowan*, 2007]. Coinciding with this warming and intensified EAC is the observation that a number of benthic invertebrates, fish and zooplankton are now found further south compared to mid-20th century [*Last et al*., 2011; *Ling*, 2008; *Pitt et al*., 2010]. We have *very high confidence* that warming has facilitated the establishment of the grazing urchin *Centrostephanus rodgersii* in eastern Tasmania during the late 1970s which has resulted in deleterious effects on macroalgal beds [*Banks et al*., 2010; *Ling*, 2008; *Ling et al*., 2008; *Ling et al*., 2009].

30.5.1.2. Key Risks and Vulnerabilities

Projected changes to the temperature of surface waters matched those of the past 50 years, with average sea temperatures in the HLSBS increasing by 0.41-1.17°C in the near term (2010-2039) and by 1.91-4.84°C over the long term (2010-2099) under the 'Business-as-usual' (BAU) RCP8.5 scenario. Under the lower-case scenario considered here (RCP2.6), projected rates of warming are much lower: 0.13 - 0.79 °C in the near term (2010-2039) and -0.09 - 1.46 °C by 2100. Risks to HLSBS from even modest warming of surface waters include changes to basin- and regional-scale ocean circulation which is *very likely* to affect the transport of organisms and water masses, primary production with implications for food webs and carbon cycling, changes in distribution, phenology and productivity of species leading to reorganization of ecosystems, and the loss of subsurface habitat to hypoxia. An additional risk exists for sub-polar areas from the loss of seasonal sea-ice. Ocean acidification will produce additional and large-scale challenges. Both primary productivity and timing of the spring bloom in this region are very sensitive to environmental change. The magnitude of planktonic production is central to higher trophic level production. Climate induced changes in stratification strength and mixed layer depth can lead to decreased or increased phytoplankton production [*Behrenfeld et al*., 2006]. The onset of spring warming within high latitude sub-regions is advancing by 2-2.5 days.decade^{-1} [*Burrows et al*., 2011]. Latitudinal shifts in the distribution of phyto- and zooplankton communities will change the day-length regimes experienced with impacts on growth and survival [*Beaugrand*, 2009; *Ito et al*., 2010; *Shoji et al*., 2011]. Alteration of the structure and composition of plankton communities will propagate through food webs because of tight trophic linkages, [*Beaugrand and Kirby*, 2010; *Beaugrand et al*., 2010; *Edwards and Richardson*, 2004]. Mechanisms are complex and tend to be non-linear, with impacts on ecosystems, fisheries and biogeochemical cycles. Climate shifts can also result in abrupt changes or rapid regime shifts in ecosystems [*Alheit*, 2009]. Climate change in the Gulf of Alaska associated with the 1976/77 PDO regime shift produced a very rapid shift in target species for commercial fisheries [*Litzow et al*., 2008]. A sudden reorganization of commercial fisheries, with attendant social and economic disruption, is a key risk and vulnerability of ongoing climate change in the region.

Alteration of thermal regimes and declining seasonal sea ice could produce changes in high latitude ecosystems that exceed those observed during the climate oscillations of the 20th century. Decreases in seasonal sea-ice in sub-polar regions are *very likely* to lead to increases in the length of the growth season and the intensity of the light available to fuel phytoplankton growth and hence to enhanced primary production and modifications of ecosystem structure [*Arrigo et al*., 2008]. In the long-term, however, primary production may decrease due to the reduced supply of nutrients to the surface layers. The decline in Arctic sea ice will open dispersal pathways between the North Atlantic and the North Pacific; large numbers of the Pacific diatom *Neodenticula seminae* were found in the North Atlantic in 1999 [*Reid et al*., 2007]. High latitude sub-regions are also vulnerable to rapid changes in ocean chemistry. There is *medium agreement* that calcifying organisms in these regions will be impacted by ocean acidification with substantial impacts on higher trophic levels although there is *limited evidence* at this point.

30.5.2. Equatorial Upwelling Systems

The largest upwelling systems are found in the equatorial regions of the eastern Pacific and Atlantic oceans (Fig. 30.1). Equatorial Upwelling Systems (EUS) produce a highly productive 'cold tongue' that stretches westward across equatorial areas. The associated upwelling is a consequence of the Earth's rotation and Easterly (westward) winds and currents which drive water northwards and southwards at the northern and southern edges of these sub-regions. As result, cold, nutrient-rich and high CO_2 waters are transported from deep waters into the surface waters, driving high levels of primary productivity which supports 4.7% of total global fisheries productivity (Table 30-1, Figure 30-1). Inter-annual and inter-decadal modes of variability (e.g. ENSO) dominate EUS, particularly in the Pacific [*Barber et al*., 1994; *Christian and Murtugudde*, 2003; *Le Borgne et al*., 2002; *McCarthy et al*., 1996; *Mestas-Nuñez and Miller*, 2006; *Pennington et al*., 2006; *Signorini et al*., 1999; *Wang et al*., 2006b]. Upwelling is reduced during

El Niño years when the trade winds cease, or even reverse, and is strengthened during the strengthened La Niña events. ENSO-periodicity controls primary productivity consequently has a strong influence over associated fisheries production [*Mestas-Nuñez and Miller*, 2006]. ENSO influences the position of the InterTropical Convergence Zone (ITCZ) at the edges of the equatorial upwelling zone and also plays a key role in determining the habitats, productivity, fisheries, and precipitation in these regions.

30.5.2.1. Observed Changes and Potential Impacts

The two EUS show similar behavior and hence are dealt with together in the one section. The average sea temperature associated with the EUS has increased significantly (0.35 and 0.45°C from 1955 to 2005 in the Pacific and Atlantic EUS, respectively; based on data from 1950 to 2009, Table 30-2). Wind speed and cloudiness have decreased in both EUS regions, with the opposite happening along the northern and southern edges (convergence zones) where cloud and wind have increased from 1955 to 2005. In the Pacific, spatial variation in SST is related to frequent El Niño Modoki or Central Pacific El Niño events [*Ashok et al*., 2007; *Lee and McPhaden*, 2010]. The faster warming of the Atlantic EUS has been associated with a weakening of upwelling [*Tokinaga and Xie*, 2011]. Sea level rise in the eastern equatorial Pacific has been minimal, with the annual rate of change <1 $mm.yr^{-1}$ since 1950 [*Church et al*., 2006].

Coral reefs in the EUS (e.g. Galápagos and Cocos islands) have relatively low species diversity and poorly developed carbonate reef frameworks in the eastern Pacific, due to the low pH and aragonite saturation of recently-upwelled waters [*Glynn*, 2001; *Manzello*, 2010; *Manzello et al*., 2008]. Prolonged periods of elevated temperature associated with El Niño have impacted corals, kelps and associated organisms, and induced several possible local extinctions [*Glynn*, 2011]. Since 1985, coral reefs from South America west to the Gilbert Islands of Kiribati have experienced the highest levels of thermal stress [*Donner et al*., 2010]. In 1982/1983, mass coral bleaching and mortality affected most of the reef systems within the eastern equatorial Pacific [*Baker et al*., 2008; *Glynn*, 1984]. Subsequent canonical El Niño and Central Pacific El Niño events in 1997/8, 2002/3, 2004/5, and 2009/10 triggered mass coral bleaching by adding to the background increases in sea temperatures due to climate change [*Donner et al*., 2010; *Obura and Mangubhai*, 2011; *Vargas-Angel et al*., 2011]. Impacts of El Niño have also interacted with other anthropogenic impacts such as fishing pressure [*Edgar et al*., 2010] further complicating the attribution of recent ecological changes to climate change.

30.5.2.2. Key Risks and Vulnerabilities

Climate models indicate that ENSO will continue to be a major driver of oceanic variability over the coming century. Consequently, superposition of a warming ocean and future ENSO activity (possibly modified frequency and intensity) may result in oceanic conditions that are different from those experienced during past El Niño and La Niña events [*Power and Smith*, 2007]. Temperatures within equatorial upwelling sub-regions are projected to continue to warm significantly, with temperatures increasing by approximately 0.8°C in the near term (2010-2039), and by approximately 3°C over the long term (2010-2099) under the BAU RCP8.5 scenario (Table 30-2). For Pacific and Atlantic EUS, differences between RCPs become clear beyond mid-century, with warming of SST under RCP2.6 being 0.43°C and 0.46°C to the much higher changes 3.01°C and 3.03°C under RCP8.5, respectively (Table 30-4). These projected increases in sea temperature will cause increasing stress and may largely eliminate key marine ecosystems such as coral reefs from this region (Box 30-1; Figure 30-12), with the temperature associated with these specific ecosystems increasing by more than 3°C by the end of the century. Further increases in atmospheric CO_2 will decrease pH and aragonite saturation of upwelling waters further. These changes in ocean chemistry will impact marine calcifiers, although many of the species from this region have already adapted to the low aragonite and calcite saturation states that result from equatorial upwelling [*Friedrich et al*., 2012; *Manzello*, 2010]. A substantial risk exists with respect to the synergistic interactions between sea temperature and declining pH, especially as to how they influence a large number of key biological processes (Box CC-OA).

There is a *low confidence* in the current understanding of how (or if) climate change will influence the behavior of ENSO and other long-term climate patterns [*Collins et al*., 2010], WG1 12.4.4.2). There is also *low agreement* between different CMIP5 models on how ocean warming will affect ENSO, with no significant change in half the models examined, and both increasing and decreasing activity in others [*Guilyardi et al.*, 2012]. These differences appear to be a consequence of the delicate balance within ENSO between dampening and amplifying feedbacks, and the different emphasis given to these processes within the different CMIP5 models [*Collins et al.*, 2010]. Other studies have looked at the interaction between the subtropical gyres (STG), EUS, and the warming of surface waters in the Pacific, with at least one study projecting the possible expansion of the STG at the expense of the EUS [*Polovina et al.*, 2011]. In the latter case, the area of equatorial upwelling within the North Pacific would decrease by 28%, and primary production and fish catch by 15%, by 2100. Many of the projected changes imply additional impacts on pelagic fisheries due to the migration of fishing grounds deriving from changing distribution of particular sea temperatures [*Bell et al.*, 2013a; *Cheung et al.*, 2010; *Lehodey et al.*, 2008; *Lehodey et al.*, 2011; *Lehodey et al.*, 2006; *Sumaila et al.*, 2011]. These projections suggest that fisheries within EUS will experience increased vulnerability due to elevated variability in space and time as a result of climate change.

30.5.3. Semi-Enclosed Seas

Semi-enclosed seas (SES) represent an subset of ocean sub-regions which are largely land-locked and consequently heavily influenced by surrounding landscapes and climates [*Healy and Harada*, 1991]. In most cases, they support fisheries significant fisheries (3.3% of global production, Table 30-1, Figure 30-1) and opportunities for other industries such as tourism. Five SES (all over 200,000 km² with single entrances < 120 km wide) are considered here. This particular geography has reduced circulation and exchange with ocean waters, and water bodies whose jurisdictions are shared by two or more neighbouring states. In many cases, the small volume and disconnected nature of SES (relative to coastal and oceanic environments) makes them highly vulnerable to both local and global stressors, especially with respect to the much reduced options for the migration of organisms as conditions change.

30.5.3.1. Observed Changes and Potential Impacts

30.5.3.1.1. Arabian Gulf

The Arabian Gulf (also referred to as the Persian Gulf), along with Red Sea, is the world's warmest sea with both extreme negative and positive temperature excursions (annual temperature range, 12-35°C). Like other SES, the Arabian Gulf is particularly vulnerable to changing environmental conditions given its landlocked nature. Trends in SST were not significant over the period 1950 to 2009 (Table 30-2) despite a large amount of variability. This may be part of larger regional and abrupt changes that occurred in the late 1980s [*Conversi et al.*, 2010]. In keeping with this, recent (1985-2002) localised analyses (e.g. Kuwait Bay) show strong and significant warming trends based, in this case, on AVHRR (NOAA) satellite data of 0.6ºC decade^{-1} [*Al-Rashidi et al.*, 2009]. There is *limited evidence* and *limited agreement* as to how this variability influences the marine ecosystems and human activities within the Arabian Gulf, although some ecosystem components (e.g. coral reefs) have been explored to some extent. The mass coral bleaching and mortality associated with 1996 and 1998 was a direct result of the sensitivity of reef-building corals to elevated sea temperatures [*Riegl*, 2002; *Riegl and Piller*, 2003], *high confidence*, Box CC-CR). These changes to coral reefs have resulted in a loss fish species that eat invertebrates while herbivorous and planktivorous fish abundances have increased [*Riegl*, 2002], *medium confidence*). Despite ecosystems there being adapted to some of the highest shallow water temperatures on earth, anthropogenic climate change is driving higher frequencies and intensities of mass coral bleaching and mortality [*Riegl et al.*, 2011]. Other biological changes (e.g. harmful algal blooms and fish kills, [*Heil et al.*, 2001]) have been associated with the increasing sea temperatures of the Arabian Gulf although attribution to increasing temperatures as opposed to other factors (e.g., water quality) is *uncertain* [*Bauman et al.*, 2010; *Sheppard et al.*, 2012].

30.5.3.1.2. Red Sea

Few studies have focused on attributing recent changes in the Red Sea to climate change (including ocean acidification). The Red Sea has warmed by 0.74°C from 1982-2006 [*Belkin*, 2009; *Raitsos et al.*, 2011] although trends over the period from 1950-2009 were not significant ($p > 0.05$, Table 30-2) due to a high degree of variability when longer periods are examined (supplementary material, [*Belkin*, 2009]. Regional trends within the Red Sea may also differ with at least one other study reporting higher rates of warming for the Central Red Sea (1.5°C [1950–1997, NOAA Extended Reconstructed SST, ERSST, v3b climatology, [*Cantin et al*., 2010]. Long-term monitoring of coral community structure and size over 20 years has shown that average coral size has declined [*high confidence*] and species latitudinal limits may have changed [*moderate confidence*]. The decline in average coral size is ascribed to significant heat-mediated bleaching in 1998, and again in 2010 [*Riegl et al*., 2012]. The patterns of this decline correlate well with the pattern of heating in the Red Sea [*Raitsos et al*., 2011] with the biggest changes being seen in the southern part of the Red Sea. Skeletal growth of the long-lived massive coral *Diploastrea heliopora* has declined significantly, very likely as a consequence of warming temperatures ($p < 0.05$, *medium confidence*).

Cantin et al. [2010] proposed that corals in the central Red Sea will cease to grow by 2070 (*medium confidence*) although this may not hold for all coral species (e.g. *Porites* and *Cyphastrea*; Cantin et al., in review, PLosOne). For example, an increase in linear extension of *Porites* corals, beginning in the 1980s was recorded in the northern Red Sea [*Heiss*, 1996], where the present local warming rate is ~0.037ºC y^{-1}, suggesting that these corals are living in sub-optimal (cooler waters) conditions and may still benefit from elevated temperature before reaching their thermal threshold, at which point growth rates would be predicted to decline as they are in many oceans. *Riegl and Piller* [2003] concluded that coral habitats at moderate depths in the Red Sea might provide important refugia from some aspects of climate change in the future. *Silverman et al*. [2007] quantified the sensitivity of net coral reef ecosystem calcification to changes in carbonate system chemistry (pH, aragonite saturation). Their results demonstrate a strong negative impact of ocean acidification on ecosystem scale calcification and decalcification, and that small changes in carbonate dissolution could have large-scale implications for the long-term persistence of carbonate coral reef systems within the Red Sea [*Silverman et al*., 2007; *Silverman et al*., 2009].

30.5.3.1.3. Black Sea

The surface waters of the Black Sea have increased by 0.96ºC from 1982 to 2006 [*Belkin*, 2009] which is consistent with other studies [*Bozkurt and Sen*, 2011; *Buongiorno Nardelli et al*., 2010] *high confidence*). As with other SES, longer data sets do not reveal a significant trend due to large-scale variability prior to 1980 which may be associated with AMO, NAO and other long-term sources of variability (Table 30-2; supplementary material, *Belkin, 2009*). *Buongiorno Nardelli et al*. [2010] observed that short-term SST variability (week-month) is strongly influenced by interactions with the overlying atmosphere, which itself is strongly influenced by the surrounding land temperatures. Freshwater discharge from rivers draining into the Black Sea has remained more or less constant since the early 1960s [*Ludwig et al*., 2009]. Increased water temperature has steadily eliminated the Cold Intermediate Layer (CIL; with temperatures below 8°C) throughout the Black Sea basin [*Oguz et al*., 2003], *high confidence*). Reduced water column mixing and upwelling during warmer winter periods has resulted in a reduced supply of nutrients to the upper layers of the Black Sea [*Oguz et al*., 2003] and expanded areas of low oxygen in the deeper parts of the Black Sea, which is the world's largest anoxic marine basin [*Murray et al*., 1989], *high confidence*). These changes have coincided with the collapse of fish stocks and the invasion by the ctenophore *Mnemiopsis leidyi* in the 1980s [*Oguz et al*., 2008], while at the same time, inputs of nutrients such as phosphate from the River Danube have decreased strongly since 1992-1993. Environmental perturbations explain the declining levels of primary productivity, phytoplankton, bacterioplankton, and fish stocks in the Black Sea from the mid-1990s [*Oguz and Velikova*, 2010; *Yunev et al*., 2007]. The Black Sea system is very dynamic and is strongly affected by non-climate stressors in addition to climate change, making attribution of detected trends to climate change difficult.

30.5.3.1.4. Baltic Sea

Temperatures in the highly dynamic Baltic Sea have increased substantially since the early 1980s, with increases of 1.35°C (1982-2006) being among the highest for SES [*Aleksandrov et al*., 2009; *Belkin*, 2009]). This increase is parallel to the increase in the adjacent North Atlantic driven mainly by AMO. Increases of this magnitude are not seen in longer records throughout the Baltic Sea (1861-2001, [*Mackenzie and Schiedek*, 2007a; b; *Mackenzie et al*., 2007]; from 1900 to 1998, [*Madsen and Hojerslev*, 2009]). The salinity of the surface and near bottom waters of the Baltic Sea (e.g. Gdansk Basin, [*Aleksandrov et al.*, 2009]; central Baltic [*Fonselius and Valderrama*, 2003; *Mollmann et al.*, 2003] decreased from 1975 to 2000, due to changing rainfall and river run-off and a reduction in the pulses of sea water (vital for oxygenation and related chemical changes) from the North Sea through its opening to the North Sea via Kattegat [*Conley et al.*, 2009; *Hanninen and Vuorinen*, 2011; *Samuelsson*, 1996] high confidence). There is a strong vertical zonation within the Baltic Sea in terms of the availability of oxygen. The shallow sub-regions of the Baltic are relatively well oxygenated. However, oxygen levels are low in the deeper basins, producing conditions where organisms and ecosystems are exposed to prolonged hypoxia.

The annual biomass of phytoplankton has declined almost threefold in the Baltic Transition Zone (Kattegat, Belt Sea) and Western Baltic Sea since 1978. The decrease in phytoplankton abundance and primary productivity since 1978 is very likely to be a response to increasing sea temperature [*Madsen and Hojerslev*, 2009], although the decreased nutrient input to the Danish Straits has almost certainly played a role ([*Henriksen*, 2009] *medium confidence*). Reduced phytoplankton production by increasing sea temperatures is expected to have a negative impact of the productivity of fisheries in the Western Baltic Sea and the transition zone [*Chassot et al.*, 2007]. Decreasing salinity in the Baltic deep basins may also affect zooplankton reproduction, especially of the copepod, *Pseudocalanus acuspes,* contributing to density-dependent decrease in growth of the commercially significant herring and sprat stocks [*Mollmann et al.*, 2003; *Möllmann et al.*, 2005], *high confidence*). The strong relationship between phytoplankton and fish production, and increasing sea temperature, decreasing salinity and other environmental factors, suggests that major changes in fisheries production may occur as sea temperatures increase and the hydrological cycle in the Baltic region is changed (*high confidence*).

A combination of climate-change-induced oceanographic changes (i.e. decreased salinity and increased temperatures) and eutrophication and overfishing have resulted in major structural changes at all trophic levels (particularly, an ecosystem regime shift [*Möllmann et al.*, 2005]) in the deep basins of the Baltic Sea. The strong relationship between primary and secondary production, and oceanography, suggests that major changes in Baltic fisheries production are very likely to occur as temperatures increase and salinities decrease. This has been demonstrated by examples such as that of the commercially important top-predator cod [*Lindegren et al.*, 2010](*medium confidence*).

30.5.3.1.5. Mediterranean Sea

The Mediterranean Sea is strongly linked to the climates of North Africa and Central Europe. SSTs within the Mediterranean SES have increased 0.43ºC from 1957 to 2008 (supplementary material, *Belkin 2009*) although analysis of data from 1950-2009 does not exhibit a significant trend ($p > 0.05$, Table 30-2) due to large fluctuations of SSTs prior to the 1980s. Increasing SST trends have been reported at a number of monitoring sites in the Mediterranean Sea (e.g. [*Calvo et al.*, 2011; *Coma et al.*, 2009; *Conversi et al.*, 2010]. In the western Mediterranean Sea, water temperatures, over the past 30–40 years, have also increased at depth [*Bethoux et al.*, 1990; *Rixen et al.*, 2005; *Vargas-Yanez et al.*, 2010]. Natural sources of variability such as the AMO and NAO, can obscure or accentuate the overall warming trend [*Marullo et al.*, 2011]. Relatively warm episodes in the 1870–1890s, 1930–1940s and since the 1990s, for example, exhibit an influence of the AMO [*Kerr*, 2000; *Moron*, 2003]. Reported temperature anomalies in the Mediterranean, often locally manifesting themselves as periods of low wind, increased water column stratification and deepening thermocline, are associated with positive phases of the NAO index [*Lejeusne et al.*, 2010; *Molinero et al.*, 2005].

Sea levels have increased rapidly in some areas over the last decades and are also strongly influenced by NAO phases. These rates have been approximately 3.4 $mm.yr^{-1}$ (1990-2009) in the NW Mediterranean [*Calvo et al.*, 2011], *high confidence*). These influences are reduced when measurements are pooled over longer time-scales resulting in a lower rate of sea level rise [*Massuti et al.*, 2008]. If the positive phase of the NAO is more frequent in the future [*Kuzmina et al.*, 2005; *Terray et al.*, 2004], then the future sea level rise may be slightly suppressed due to atmospheric changes [*Jorda et al.*, 2012]. As temperatures have increased, the Mediterranean has become more saline (+0.035 to 0.040 psu over 1950-2000, [*Rixen et al.*, 2005]) and the length of the stratification period persisted twice as long in 2006 than it did in 1974 [*Coma et al.*, 2009].

Conditions within the Mediterranean Sea changed abruptly and synchronously with similar changes across the North, Baltic, and Black Seas in the late 1980s [*Conversi et al.*, 2010], which possibly explains the lack of trend in SES Sea surface data when examined over 50-60 years (Table 30-2). These changes in physical conditions (increased temperature, higher sea level pressure, positive NAO index) also coincided with step-changes in the diversity and abundance of zooplankton, decreases in stock abundance of anchovies, and the frequency of red tides and, increases in mucilage outbreaks [*Conversi et al.*, 2010]. Mucilage outbreaks are strongly associated with warmer and more stratified water columns (*high confidence*), and lead to a greater abundance and diversity of marine microbes and potentially disease organisms [*Danovaro et al.*, 2009]. Increasing temperatures are also driving the northward spread of warm-water species (*medium confidence*) such as the sardine, *Sardinella aurita* [*Sabates et al.*, 2006; *Tsikliras*, 2008], and contributed to the fast spread of the coral *Oculina patagonia* [*Serrano et al.*, submitted]. The recent spread of warm-water species that have invaded through the Straits of Gibraltar and through the Suez Canal, into cooler northern areas is leading to “tropicalisation” of Mediterranean fauna [*Ben Rais Lasram and Mouillot*, 2008; *Bianchi*, 2007; *CIESM*, 2008; *Galil*, 2008; 2011] (*high confidence*). Warming since the end of the 1990s has accelerated the spread of tropical invasive species from the eastern Mediterranean basin [*Raitsos et al.*, 2010]

In addition to general patterns of warming, periods of extreme temperatures have had large-scale impacts on Mediterranean marine ecosystems. Unprecedented mass mortality events that affected at least 25 prominent invertebrate species occurred during the summers of 1999, 2003 and 2006 across hundreds of kilometres of coastline in the NW Mediterranean Sea [*Calvo et al.*, 2011; *Cerrano et al.*, 2000; *Crisci et al.*, 2011; *Garrabou et al.*, 2009] *very high confidence*). Events coincided with either short periods (2-5 days, 2003, 2006) of high sea temperatures (27°C) or longer periods (30-40 days) of modestly high temperatures (24°C, 1999; [*Bensoussan et al.*, 2010; *Crisci et al.*, 2011]). Impacts on marine organisms have been reported in response to the extreme conditions during events such as those in 1999, 2003 and 2006 in the Mediterranean (e.g. gorgonian-corals mortality [*Coma et al.*, 2009], shoot mortality and anomalous flowering of seagrasses [*Diaz-Almela et al.*, 2007; *Marba and Duarte*, 2010], *high confidence*). Increasing sea temperatures are very likely to increase the frequency and intensity of these types of heat stress events (*high confidence*).

Long-term data series (over several decades) to measure the rate of acidification in the Mediterranean Sea are scarce [*Durrieu de Madron et al.*, 2011]. Recent re-analysis, however, has concluded that the pH of Mediterranean waters has decreased by 0.05-0.14 pH units since the preindustrial period [*Luchetta et al.*, 2010; *Touratier and Goyet*, 2011], medium confidence). Even the deepest Mediterranean water is contaminated by anthropogenic CO_2, which the greatest relative changes in pH for an entire water column [*Touratier and Goyet*, 2011]. Studies that have explored the impact of ocean acidification on the biology and ecology of the Mediterranean Sea are rare although insights have been gained by studying natural CO_2 seeps at Mediterranean sites such as Ischia in Italy [*Hall-Spencer et al.*, 2008]. Major changes to Mediterranean organisms and ecosystems were revealed for high CO_2 environments with calcifying organisms (e.g. molluscs, calcareous algae) being negatively affected while seagrasses and some macroalgae appeared to benefit.

30.5.3.2. Key Risks and Vulnerabilities

SES are highly vulnerable to changes in global temperature on account of their small volume and landlocked nature. Consequently, SES are *virtually certain* to respond faster than other parts of the ocean (*high confidence*). Risks to ecosystems within SES are *very likely* to increase as water columns become further stratified under increased warming, promoting hypoxia at depth and reducing nutrient supply to the upper water column (*medium evidence, high agreement*). The impact of rising temperatures on SES is exacerbated by their vulnerability to other human impacts such as overexploitation, pollution and enhanced run-off from modified coastlines. Due to a mixture of global and local human stressors, key fisheries have undergone fundamental changes in their abundance and distribution over the past 50 years. A major risk exists for SES from projected increases in the frequency of temperature extremes that drive mass mortality events, increasing water column stabilisation leading to reduced mixing, and resulting changes to the distribution and abundance of marine organisms. The vulnerability of marine ecosystems, fisheries and human communities associated with the SES will continue to increase as global temperatures increase.

There is *very high confidence* that sea temperatures within the five SES will increase further under even moderate Representative Concentration Pathways (RCP). Under BAU (RCP 8.5; Table 30-4), sea temperatures in the SES are projected to increase by 0.93-1.24°C by 2039 and by 3.45-4.37°C by the end of the century (Table 30-4). The greatest increases are projected for the surface waters of the Baltic Sea (4.26°C) and Arabian Gulf (4.33°C), with lower yet substantial amounts of warming in the Red Sea (3.45°C). The heat content added to these small oceans is *very likely* to increase stratification of the water column, which will reduce the nutrient supply to the upper layers of the water column, reducing primary productivity and driving major changes to the structure and productivity of fisheries. Reduced mixing and ventilation, along with increased microbial metabolism, will *very likely* expand hypoxia and increase the size and number of 'dead zones'. Changing rainfall intensity is likely to also have strong influences on the physical and chemical conditions within SES, in some cases combining with climate change to transform these areas. These changes are likely to increase the risk of reduced O_2 levels to Baltic and Black Sea ecosystems, which is *very likely* to affect fisheries. Based on responses to temperature extremes seen over the past 30 years, these changes will increase the frequency and intensity of impacts arising from heat stress, such as the mass mortality of benthic organisms in the Mediterranean during the summers of 1999, 2003 and 2006, and the Arabian Gulf in 1996 and 1998. Similar projections to those seen in 30.8.4 can be applied to the coral reefs of the Arabian Gulf and the Red Sea, where temperatures are *very likely* to increase above established thresholds for mass coral bleaching and mortality (*high confidence*; Figure 30-12).

30.5.4. Coastal Boundary Systems

The Coastal Boundary Systems (CBS) are highly productive regions, comprising 10.6% of primary production and 28.0% of global fisheries production (Table 30-1, Figure 30-1). CBS regions are also bounded by the sub-regions of the Pacific, Atlantic and Indian oceans, except in coastal areas associated with the EBUEs. Within these sub-regions, the CBSs are dominated by powerful currents such as the Kuroshio (Pacific) and the Gulf Stream (Atlantic), and are strongly influenced by monsoons (e.g. Asian-Australian and African monsoons). The CBS includes the marginal seas of the NW Pacific, Indian, Atlantic and comprises Bohai/Yellow Sea, East China Sea, South China Sea and South-east Asia seas (e.g. The Timor, Arafura, Sulu, and northern coast of Australia) in the Pacific, and the Arabian Sea, Somali Current system, East Africa coast, small archipelagic states, Mozambique Channel and Madagascar in the Indian Ocean, and the Caribbean Sea and Gulf of Mexico in the Atlantic Ocean.

30.5.4.1. Observed Changes and Potential Impacts

Many ecosystems within the CBS are strongly affected by the local activities of often dense coastal human populations. Activities such as the overexploitation of fisheries, unsustainable coastal development and pollution have resulted in the wide-spread degradation of CBS ecosystems [*Burke et al.*, 2002; *Burke et al.*, 2011]. These influences have combined with steadily increasing ocean temperature and acidity to drive major changes to a range of important ecosystems over the past 50 years. Understanding the interactions between climate change and non-climate change drivers is a central part of the detection and attribution process within the CBS.
Overall, CBSs have warmed by 0.46-0.67°C from 1955 to 2005 (Table 30-2), although changes within the Gulf of Mexico/Caribbean sub-region were not significant over this period. Key sub-regions within the CBS such as Coral Triangle and Western Indian Ocean have warmed by 0.65 and 0.50°C respectively from 1955-2005 (calculated using data from 1950-2009, Table 30-2). Rates of sea level rise vary from low (2-3 mm year^{-1}, Caribbean) to very high rates (10 mm year^{-1}, SE Asia; 30.3.1.2). Ocean acidification also varies from region to region, influenced by oceanographic and coastal processes (Figure 30-6 A-D, Figure 30-7) which often have a large human component.

30.4.4.1.1. Bohai/Yellow Sea/East China Sea

Bohai/Yellow Sea and East China Sea (ECS) are shallow marginal seas along the edge of the NW Pacific that are strongly influenced by Kuroshio, the East Asian Monsoon (EAM), and major rivers such as Yellow River and Changjiang (Yanktze) River. The Kuroshio intrusion influences the associated marginal seas [*Matsuno et al.*, 2009], providing abundant nutrients which support high levels of primary productivity [*Chen et al.*, 1996; *Wong et al.*, 2001; *Wong et al.*, 2000]. The ecosystems of the ECS are heavily impacted by anthropogenic pressure factors (e.g., overfishing and pollution) which tend to compound the impacts of climate change.

SST within the ECS increased rapidly since the early 1980s [*Cai et al.*, 2011.; *Jung*, 2008; *Lin et al.*, 2005; *Tian et al.*, 2012]. The largest increases in SST have occurred in the ECS in winter (1.96°C, 1955-2005) and Yellow Sea in summer (1.10°C, 1971-2006 [*Cai et al.*, 2011.]. These changes in SST are closely linked to the weakening of the EAM (e.g. [*Cai et al.*, 2011.; *Cai*, 2006.; *Tang et al.*, 2009], and increasing warmth of the Kuroshio Current [*Qi*, 2010; *Wu et al.*, 2012; *Zhang et al.*, 2011]. At the same time, dissolved oxygen has decreased [*Jung*, 2008; *Lin et al.*, 2005; *Qi*, 2010] with an associated increase in the size of the hypoxic areas (≤60 mmol kg^{-1}) in coastal areas of Yellow Sea/ECS [*Jung*, 2008; *Ning et al.*, 2011; *Tang*, 2009].

There is *robust evidence* and *high agreement* that primary productivity, biomass yields and fish capture rates are declining within the ECS [*Lin et al.*, 2005; *Tang*, 2009; *Tang et al.*, 2003]. There is *medium evidence and medium agreement* that these are being driven by climate change and human pressures. Warm-water zooplankton species have expanded northward in the Changjiang River Estuary as water temperatures have increased [*Ma et al.*, 2009]. Fluctuations in herring abundance also appear to closely track SST regime shifts within the Yellow Sea [*Tang*, 2009]. The proportion of warm water species relative to warm temperate species from plankton to fish species in the Changjiang River Estuary (extending to the south Taiwan Strait) have changed in the past decades [*Lin and Yang*, 2011; *Ma et al.*, 2009; *Zhang et al.*, 2005]. Meanwhile, the frequency of harmful algal blooms (HAB) and blooms of the Giant Jellyfish (*Nemopile manomurai*) in the offshore area of ECS have increased and have been associated with ocean warming and other factors such as eutrophication [*Cai and Tan*, 2010; *Tang*, 2009; *Ye and Huang*, 2003]. While attribution of these changes to anthropogenic climate change is complicated by the increasing influence of non-climate related human activities, many of these changes are consistent with those expected as sea temperatures increase.

30.5.4.1.2. South China Sea

The South China Sea (SCS) is surrounded by continental areas and a large number of islands, and is connected to the Pacific, ECS, and Sulu Sea by straits such as the Luzon and Taiwan Strait. The region is greatly influenced by cyclones/typhoons, and by the Pearl, Red and Mekong Rivers. The region has a distinct seasonal circulation and is greatly influenced by the southwest monsoon (in summer), the Kuroshio Current and northeast monsoon (in winter). The SCS includes significant commercial fisheries areas and includes coral reefs, mangroves and seagrasses.

The surface waters of the SCS have been warming steadily from 1945-1999 [*Li et al.*, 2002; *Liu et al.*, 2007] with the annual mean SST in the central SCS increasing by 0.92°C (1950-2006) [*Cai et al.*, 2008,], a rate similar to that observed for the entire Pacific CBS from 1955-2005 (calculated using data from 1950-2009, 0.67°C, Table 30-2). Significant freshening in the SCS intermediate layer since the 1960s has been observed [*Liu et al.*, 2007]. The temperature change of the upper layers of the SCS has made a significant contribution to sea level variation which is spatially non-homogeneous and varies in time [*Cheng and Qi*, 2007; *Li et al.*, 2002].

Identifying a clear climate change impact within the SCS is difficult due to complexity of other factors and their interactions (e.g. local human stressors, and ‘natural’ climate variability such as EAM, ENSO and PDO). There is *limited evidence* and *medium agreement*, however, that changing sea temperatures have influenced the abundance of phytoplankton, benthic biomass, cephalopod fisheries and the size of demersal trawl catches in northern SCS [*Ning et al.*, 2008]. Coral reefs and mangroves are degrading rapidly as a result of both climate change and non-climate change factors (Box CC-CR)[*China-SNAP*, 2011]. Elevated SSTs have triggered mass coral bleaching and mortality of coral reefs within the SCS in 1998 and 2007 [*Li et al.*, 2011; *Yu et al.*, 2006]. On the other hand, warming of ocean waters has very likely favourably influenced the establishment of a high latitude, non-carbonate coral community in Daya Bay in the northern SCS, although this community has recently degraded due to local anthropogenic stresses [*Chen et al.*, 2009; *Qiu et al.*, 2010].

30.5.4.1.3. Southeast Asian seas

The South-east Asian Seas (SASs) have a complex island and archipelago domain which interacts with the westward flow of the North Equatorial current and the Indonesian through-flow (Figure 30-1). A large part of this region is referred to as the 'Coral Triangle' [*Veron et al.*, 2009] and is the world's most biologically diverse marine area and includes parts of Malaysia, Indonesia, Philippines, Timor L'este, Solomon Islands, and Papua and New Guinea. Sea temperatures increased significantly over the period 1985-2006 [*McLeod et al.*, 2010; *Peñaflor et al.*, 2009] although with considerable spatial variation. Trends examined over longer periods (1955-2005) also show significant warming (+0.65°C, $p < 0.05$; Table 30-2, calculating using data from 1950-2009). Sea level is increasing by 10 $mm.yr^{-1}$ in a significant proportion of this region [*Church et al.*, 2006; *Church et al.*, 2004; *Green et al.*, 2010]. Like other tropical areas in the world, coral reefs within SASs have experienced periods of elevated temperatures which have driven several mass coral bleaching and mortality events since the early 1980s (Figure 30-12), with the most recent occurred during the warm conditions associated with 2010 [*Krishnan et al.*, 2011; *McLeod et al.*, 2010]. There is *robust evidence* and *high agreement* that these changes are the result of increasing ocean temperatures and are very likely to be a consequence of anthropogenic climate change (*high confidence*, Box CC-CR; WG1 10.4.1). Calcification rates of some key organisms (e.g., reef-building corals [*Tanzil et al.*, 2009] have slowed over the past two decades with increased sea temperature although the cause remains uncertain due to the possible influence of ocean acidification in these changes. While a large part of the decline in coral reefs has been due to rising local stresses (principally destructive fishing, declining water quality, and overexploitation of key reef species), there is high agreement that projected increases in SST represent a major challenge for these valuable ecosystems [*Burke and Maidens*, 2004; *Burke et al.*, 2002].

30.5.4.1.4. Arabian Sea and Somali Current

The Arabian Sea and Somali current are relatively productive ocean areas, being strongly influenced by upwelling and the monsoonal system. Wind-generated upwelling enhances primary production in the western Arabian Sea [*Prakash and Ramesh*, 2007]. Several key fisheries within this region are under escalating pressure from both fishing and climate change. Sea water temperature has increased by 0.18ºC and 0.26ºC in the Arabian Sea and Somali current, respectively, over the period 1982-2006 (HadSST2, [*Belkin*, 2009; *Rayner et al.*, 2003], which is consistent with the overall rate of warming of the Western Indian Ocean portion of the CBS from 1955-2005 (0.50ºC, using data from 1950-2009, Table 30-2). Salinity of surface waters in the Arabian Sea has also increased by 0.5-1.0% over the past 60 years (Figure 30-6D) due to increased evaporation from warming seas and contributions from the outflows of the saline Red Sea and Arabian Gulf.

The aragonite saturation horizon in the Arabian Sea and Bay of Bengal is now 100 to 200 m shallower than it was in preindustrial times as a result of ocean acidification [*Feely et al.*, 2004]. More than 50% of oxygen minimum zones (OMZs) and dead zones in the world oceans [*Diaz and Rosenberg*, 2008] occur in the Arabian Sea (Figure 30-8) and Bay of Bengal [*Helly and Levin*, 2004] where, unlike other sub-regions, OMZs have not expanded since the 1960s [*Karstensen et al.*, 2008]. As in other tropical sub-regions, increasing sea temperatures have increased the frequency of mass coral bleaching and mortality within this region [*Goreau et al.*, 2000; *Wilkinson*, 2004; *Wilkinson and Hodgson*, 1999]. Shoaling of the aragonite saturation horizon is likely to affect a range of organisms and processes, such as the depth distribution of pteropods in the western Arabian Sea [*Hitchcock et al.*, 2002; *Mohan et al.*, 2006]. The information regarding the impacts of climate change within this region is undeveloped and suggests that important physical, chemical and biological responses to climate change need to be the focus of further investigation.

30.5.4.1.5. East Africa coast and Madagascar

Oceanic conditions within the East Africa and Madagascar region influence on the coastal conditions associated with Kenya, Mozambique, Tanzania, Madagascar, La Réunion, Mayotte, and three archipelagos (Comores, Mauritius and the Seychelles). Like the north-west section of the Indian Ocean, sea temperatures are increasing rapidly (*high confidence*, $p < 0.05$). Changes in surface salinity vary with the location along the East African coastline. Periods of heat stress over the past 20 years has triggered mass coral bleaching and mortality on coral reef ecosystems with within this region [*Ateweberhan and McClanahan*, 2010; *Ateweberhan et al*., 2011; *McClanahan et al*., 2009a; *McClanahan et al*., 2009b; *McClanahan et al*., 2009c; *McClanahan et al*., 2007]. Steadily increasing sea temperatures have also produced anomalous growth rates in long-lived corals such as *Porites* (*high confidence,* $p < 0.05$)[*McClanahan et al*., 2009b]. Differences in the susceptibility of reef-building corals to stress from rising sea temperatures has also resulted in changes to the composition of coral (*high confidence,* $p < 0.05$, [*McClanahan et al*., 2007] and benthic fish communities (*high confidence*, $p < 0.05$, [*Graham et al*., 2008; *Pratchett et al*., 2011a], which is *very likely* to alter species composition and potentially the productivity of coastal fisheries (*robust evidence, high agreement*, *high confidence*)[*Jury et al*., 2010], although there may be a significant lag between the loss of coral communities and the subsequent changes in the abundance and community structure of fish ($p < 0.05$, [*Graham et al*., 2007]. Attempts to slow these impacts have included the establishment of marine protected areas and changes to fishing management [*Cinner et al*., 2009; *Jury et al*., 2010; *MacNeil et al*., 2010; *McClanahan et al*., 2008].

30.5.4.1.6. Gulf of Mexico and Caribbean Sea

The Caribbean Sea and the Gulf of Mexico form a semi-contained maritime province within the Western Atlantic. These areas are dominated by a range of activities including mineral extraction, fishing and tourism which provide employment and opportunity for over 100 million people who live in coastal areas of the US, Mexico and a range of other Caribbean nations [*Adams et al*., 2004]. The Caribbean Sea and the Gulf of Mexico have warmed by 0.50°C and 0.31°C respectively from 1982 to 2006 [*Belkin*, 2009; *Sherman et al*., 2009]. Warming trends are not significant from 1950-2009 (Table 30-2) which may be partly due to warming being spatially heterogeneous and the enclosed nature of this region making it strongly influenced by long-term variability in a similar way to that seen with respect to the SES sub-regions (30.5.3.1). The Caribbean region has experienced a sustained decrease in the aragonite saturation state from 1996 to 2006 [*Gledhill et al*., 2008]. Sea levels within the Gulf of Mexico and Caribbean Sea have increased at the rate of 2-3 mm y^{-1} from 1950 to 2000 [*Church et al*., 2004; *Zervas*, 2009].

Understanding influences of climate change on ocean ecosystems in this region is complicated by confounding influence of growing human populations and activities. The recent expansion of the seasonal hypoxic zone has been attributed to nitrogen inputs driven by land management [*Donner et al*., 2004; *Turner and Rabalais*, 1994] and changes to river flows, wind patterns, and thermal stratification of Gulf waters, which are likely to increase the size of the Gulf of Mexico “dead zone” [*Justic et al*., 1996; *Justic et al*., 2007; *Levin et al*., 2009; *Rabalais et al*., 2009; *Rabalais et al*., 2010]. Coastal pollution and fishing have also had increasing impacts that have potentially interacted with the influence of climate change on ocean ecosystems within this region (WGII's Ch5, Ch29).

A combination of local and global disturbances has driven the large-scale loss of reef-building corals across the Caribbean Sea since the late 1970s [*Gardner et al*., 2003; *Hughes*, 1994]. Record thermal stress in 2005 triggered the largest mass coral bleaching and mortality event on record for the region, damaging coral reefs across hundreds of km^2 in the eastern Caribbean Sea [*Donner et al*., 2007; *Eakin et al*., 2010]. Similar conditions and impacts on coral reefs occurred in 2010. Increasing sea temperatures has also been implicated in the spread of disease organisms in the Caribbean [*Harvell et al*., 2002b; *Harvell et al*., 1999; *Harvell et al*., 2004] and some introduced species [*Firth et al*., 2011]. As in other sub-regions, pelagic fish species are sensitive to changes in sea temperature and modify their distribution and abundance [*Muhling et al*., 2011]. Ocean acidification may also be altering patterns of fish recruitment although direct evidence for impacts on Caribbean species is lacking [*Dixson et al*., 2010; *Dixson et al*., 2008; *Munday et al*., 2009].

30.5.4.2. Key Risks and Vulnerabilities

At least 850 million people live within 100 km of CBS regions (i.e. number living within 100 km of coral reefs is 850 million and is therefore a minimum estimate given there are other ecosystems other than coral reefs, *Burke et al.* [2011]) from where they derive a range of benefits from food, coastal protection, cultural services, and income from industries such as fishing and tourism. Marine ecosystems within the CBS are sensitive to increasing sea temperatures (Figure 30-12), although detection and attribution is complicated by the significant influence and interaction with non-climate change stressors (water quality, over-exploitations of fisheries, coastal degradation; Box CC-CR). Warming is *likely* to have changed the primary productivity of ocean waters, placing valuable ecosystems and fisheries at risk within the ECS. Other risks include the expansion of hypoxic conditions and associated dead zones in many parts of CBS. Given the impact on coastal ecosystems and fisheries, these changes are *very likely* to increase the vulnerability of coastal communities throughout the CBS.

Sea temperatures are rapidly increasing within many parts of the CBS ecosystems, which will continue over the next few decades and century. Sea temperatures are projected to change by 0.34-0.50°C in the near–term (by 2039) and by 0.23 - 0.74°C in the long –term (by 2099) under the lowest RCP scenario (RCP2.6). Under BAU RCP8.5, CBS sea temperatures are projected to increase 0.62-0.85°C by 2039 and 2.44 – 3.32°C by 2099 (Table 30-4). Given the large-scale impacts (e.g. mass coral bleaching and mortality events) have occurred in response to much smaller changes in the past over the CBS regions (0.10-0.67°C from 1955 to 2005, Table 30-2), the projected changes of 2.44 – 3.32°C by 2099 are *very likely* to have large-scale and negative impacts on structure and function of many CBS ecosystems (Figure 30-12). It is *virtually certain* that fishery composition will change with *robust evidence* and *high agreement* that catch rates and productivity of many fisheries will be *very likely* to decrease as waters warm, acidify and stratify, and as crucial habitat associated with ecosystems such as coral reefs degrades. These changes are *very likely* to increase the vulnerability of millions of people who live in coastal communities and depend directly on fisheries and other ecological goods and services.

It is *very likely* that coral reef ecosystems will not survive changes in sea temperature beyond an additional increase of 1°C (Box CC-CR; Figure 30-12). Combining the known sensitivity of coral reefs within the Caribbean and Coral Triangle sub-regions [*Hoegh-Guldberg*, 1999; *Strong et al.*, 1997; *Strong et al.*, 2011], with the exposure to higher temperatures that are projected under medium (RCP4.5) to high (RCP8.5) scenarios, reveals that both coral reef rich regions are *virtually certain* to experience levels of thermal stress that cause coral bleaching every 1-2 years by the mid to late part of this century (*robust evidence, high levels of agreement, very high confidence,* Figure 30-5 A,B; Figure 30-12A,B). The frequency of mass mortality events (DHM > 5; Figure 30-11 A,C) climbs towards events that occur every 1-2 years by mid to late of this century under low to high climate change scenarios (*robust evidence, high levels of agreement, very high confidence,* [*Donner et al.*, 2005; *Frieler et al.*, 2012; *Hoegh-Guldberg*, 1999]. Mass mortality events that impact coral reefs will result in changes to community composition in the short-term (2010-2039)[*Adjeroud et al.*, 2009; *Berumen and Pratchett*, 2006] and a continuing downward trend in reef-building coral stocks in the longer term [*Baker et al.*, 2008; *Bruno and Selig*, 2007; *Gardner et al.*, 2003].

[INSERT FIGURE 30-12 HERE
Figure 30-12: Annual maximum proportions of reef pixels with Degree Heating Months (Donner et al. 2007; DHM) ≥ 1 (coral bleaching) and DHM ≥ 5 (bleaching across 100% of affected areas with significant mortality, Eakin et al. 2010) for each of the six coral regions (Figure 30-3) have been depicted as bar graphs for the period 1870-2009. This part of the graph is derived from the HadISST 1.1 data set. The black line plotted on top of the bar graphs is the maximum annual area value for each decade over the period 1870-2009. This value is continued through 2010-2099 using CMIP-5 data and splits into the four Representative Concentration Pathways (RCP 2.6, 4.5, 6.0 and 8.5). DHMs were produced for each of the four RCPs using the ensembles of CMIP models. From these global maps of DHMs the annual percentage of grid cells with DHM ≥ 1 and DHM ≥ 5 were calculated for each coral region. These data were then grouped into decades from which the maximum annual proportions were derived. The plotted lines for 2010-2099 are the average of these maximum proportion values for each RCP. Monthly SST anomalies are derived using a 1985-2000 maximum monthly mean (MMM) climatology derived in the calculations for Figure 30-4. This was done separately for HadISST 1.1 and each of the CMIP-5 models and each of the four RCPs, at each grid cell for each region. DHMs are then derived by adding up the monthly anomalies using a 4 month rolling sum.]

30.5.5. Eastern Boundary Upwelling Ecosystems

The Eastern Boundary Upwelling Ecosystems (EBUE) includes the California, Peru/Humboldt, Canary/NW Africa, and Benguela. They are highly productive sub-regions involving primary productivity that may exceed 1,000 g C m^{-2} y^{-1}. Although these provinces comprise <2% of the world ocean area, they contribute nearly 7% of marine primary production (Table 30-1, Figure 30-1) and more than 20% of the world's capture fisheries [*Pauly and Christensen*, 1995], which are dominated by planktivorous sardine, anchovy, and horse/jack mackerel, and piscivorous benthic-fish such as hake. This level of productivity is a result of large-scale atmospheric pressure gradients and wind systems which advect surface waters offshore (Box 30-1), which are then replaced with cold, nutrient-rich waters upwelled from depth into coastal euphotic zones [*Chavez*, 2011; *Chavez and Messie*, 2009; *Chavez et al.*, 2011]. At the same time, upwelling waters also have high concentrations of CO_2 as well as low pH and reduced concentrations of oxygen, trends that are likely to increase as atmospheric CO_2 increases [*Feely et al.*, 2008; *Gruber*, 2011]. Nutrient input stimulates primary production from phytoplankton blooms that are transferred to mid and upper trophic levels, resulting in substantial fish, seabird and marine mammal populations. As a result, EBUEs are considered "hotspots" of biodiversity [*Block et al.*, 2011].

30.5.5.1. Observed Changes and Potential Impacts

The historical importance of EBUE fisheries has resulted in extensive studies of their coupled climate-ecosystem dynamics (e.g. California Current). Decadal variability poses challenges to the detection and attribution of changes within the EBUEs to climate change although there are a number of long-term studies that have been able to provide insight into the patterns of change and their causes. Like other ocean sub-regions, EBUEs are projected to warm under climate change, experiencing increased stratification as well as periods of intensified upwelling, and altered wind fields as westerly winds shift polewards. However, cooling is also predicted for some EBUEs, resulting from the intensification of wind-driven upwelling [*Bakun*, 1990]. There is *limited* agreement on a broad response by EBUEs to climate change over past decades with considerable variability in warming and cooling both within and among systems [*Burrows et al.*, 2011; *Demarcq*, 2009], see 30.3.1.1 Table 30-2). The California and Canary Currents have warmed by 0.61 and 0.45°C ($p \leq 0.05$, 1950-2009; Table 30-2) respectively, while there has been no significant change in the temperature of the surface waters of the Benguela and Humboldt Currents since from 1950-2009 ($p > 0.05$, Table 30-2). These trends match shorter term trends (or lack of trends) for EBUs using Pathfinder version 5 data (Table 1, [*Demarcq*, 2009]. These differences between EBUEs are *likely* to be the result of differences in the influence of long-term variability and the specific responses of coastal wind systems to warming (Figure 30-6A) although an analysis of wind data over the same period did not pick up clear trends [*Demarcq*, 2009].

How climate change is likely to influence ocean upwelling is central to resolving ecosystem and fishery responses within each EBUE. There is considerable debate, however, as to whether or not climate change will drive an intensification of upwelling (e.g. [*Bakun et al.*, 2010; *Narayan et al.*, 2010]) in all regions. Discussion of the various hypotheses for how climate change is likely to affect coastal upwelling is presented in Box 30-1. EBUEs are also areas of naturally low pH and high CO_2 concentrations due to upwelling, and consequently may be vulnerable to ocean acidification and its synergistic impacts. A full understanding of the impacts of ocean acidification is discussed elsewhere (Box CC-OA; 6.2.2, 6.3.4, [*Kroeker et al.*, 2013], WG1 6.4).

30.5.5.1.1. Canary Current

Part of the North Atlantic STG, the Canary Current extends from northern Morocco southwestward to the North Atlantic Equatorial Current. It is linked with the Portugal Current (which is sometimes considered part of the Canary Current) upstream and extends downstream to the Atlantic Equatorial Current. The coastal upwelling system, however, is limited to a narrow belt along the Saharan west coast to the coast of Guinea, with the most intense upwelling centrally, along the coast of Mauretania (15-20ºN) and Morocco (21-26°N). Total fish catches, comprising mainly coastal pelagic sardines, sardinellas, anchovies and mackerel, have fluctuated around 2 million tons.yr^{-1} since the 1970s (http://www.seaaroundus.org/lme/27.aspx). Contrasting with the other EBUEs, fishing productivity is modest, probably due to the legacy of uncontrolled fishing in the 1960s [*Arístegui et al.*, 2009].

Most observations suggest that the Canary current is warming at both local [*Demarcq*, 2009] and regional [*Belkin*, 2009] scales since the early 1980s with analysis of HadSST 1.1 data from 1950-2009 indicating warming of 0.45°C from 1955 to 2005 ($p<0.05$; Table 30-2) with a 20% and 45% decrease in the strength of upwelling in winter and summer respectively from 1967 to 2006 [*Gómez-Gesteira et al.*, 2008]. This is consistent with a decrease in wind strength over the past 60 years (Figure 30-6A), which reduces the upwelling and nutrient concentrations, and the supply of iron-laden dust from the Sahara [*Alonso-Pérez et al.*, 2011]. There is *medium evidence* and *agreement* that primary production in the Canary Current has decreased over the past two decades [*Arístegui et al.*, 2009; *Demarcq*, 2009], Table 1) contrasting trends apparent of nearby region of NW Spain [*Bode et al.*, 2011]. Satellite chlorophyll records (SeaWifs, MODIS) are relatively short, making it difficult to distinguish longer-term patterns of variability from the influence of climate change (*low confidence*)[*Henson et al.*, 2010]. There is also substantial interannual to decadal-scale variability in the fish catches in this system, and catch trends (1950-2007), which is not entirely consistent with these patterns of change in temperature, upwelling, or nutrient supply [*Arístegui et al.*, 2009; *Zeeberg et al.*, 2008].

30.5.5.1.2. Benguela Current

The Benguela Current originates from the eastward-flowing, cold South Atlantic Current, flows northward along the African southwest coast, and is bounded north and south by the warm-water Angola and Agulhas Currents, respectively. Upwelling is strongest and most persistent toward the center of the system in the Lüderitz-Orange River upwelling cell [*Hutchings et al.*, 2009]. Fish catch reached a peak in the late 1970s at 2.8 million tons.yr^{-1} (http://www.seaaroundus.org/lme/29/1.aspx), before declining to around 1 million tons.yr^{-1} (present) as a combined result of overfishing and inter-decadal environmental variability [*Cury and Shannon*, 2004; *Heymans et al.*, 2004; *Hutchings et al.*, 2009]. Commercial fisheries currently comprise sardine, anchovy and horse mackerel, and hake.

Most research in the Benguela Current has focused on fisheries and oceanography, with little emphasis on climate change. As with the other EBUEs, strong inter-annual and inter-decadal variability in physical oceanography make the detection and attribution of biophysical trends to climate change difficult. Nevertheless, physical conditions of the Benguela are highly sensitive to climate variability over a range of scales, and especially to atmospheric teleconnections that alter local wind stress [*Hutchings et al.*, 2009; *Leduc et al.*, 2010; *Richter et al.*, 2010; *Rouault et al.*, 2010]). Consequently, there is *medium agreement* that the Benguela system will change as a result of climate change [*Demarcq*, 2009].

There is no significant trend in the temperature of the surface waters of the Benguela Current from 1950 to 2009 ($p > 0.05$; Table 30-2) although shorter records show a decrease in the temperature of the south-central Benguela (0.35–0.55 ºC.decade^{-1} [*Rouault et al.*, 2010] or the whole Benguela region (total decrease of 0.24ºC, *Belkin* [2009]). These differences between short versus long records indicate the substantial influence of long-term variability on the Benguela system, reflected by the index of variability shown in Table 30-2. Information on other potential climate-change impacts within the Benguela is sparse. Sea-level rise is similar to the global mean, although it has not been measured rigorously within the Benguela [*Veitch*, 2007]. Although upwelling water in the northern and southern portions of the Benguela exhibits elevated and suppressed $p\mathrm{CO_2}$, respectively [*Santana-Casiano et al.*, 2009]), the consequences of changing upwelling intensity remain poorly explored with respect to ocean acidification. Finally, while periodic hypoxic events in the Benguela are driven largely by natural advective processes, these may be exacerbated by future climate change [*Bakun et al.*, 2010; *Monteiro et al.*, 2008].

Despite its apparent sensitivity to environmental variability, there is no published evidence from the Benguela EBUE that attributes marine ecological impacts to climate change with any degree of confidence [*Poloczanska et al.*, 2013]. For example, pelagic fish [*Roy et al.*, 2007], benthic crustaceans [*Cockcroft et al.*, 2008] and seabirds [*Crawford et al.*, 2008] have demonstrated general eastward range shifts around the Cape of Good Hope. Although these may be associated with increased upwelling along the South African south coast, specific studies that attribute these changes to anthropogenic climate change are lacking.

30.5.5.1.3. California Current

The California Current spans ~23° of latitude from central Baja California, Mexico, to central British Columbia, linking the North Pacific Current (Westwind Drift) with the North Equatorial and Kuroshio currents, to form the North Pacific Gyre. High productivity driven by advective transport and upwelling [*Checkley and Barth*, 2009; *Chelton et al.*, 1982; *Hickey*, 1979] supports well-studied ecosystems and fisheries. Fish catch data from the California Current since 1950 is about 0.6 million tons.yr^{-1} (http://www.seaaroundus.org/lme/3.aspx) which makes it the lowest catch of the four EBUEs. However, a major fraction of the catches is on one higher trophic level than in the other EBUEs, i.e. more on piscivores than planktivores. Sardine (~47,000 metric tons.yr^{-1}) and squid (~65,000 metric tons.yr^{-1}) dominated the commercial catch of lower trophic level fisheries in the California Current (2000-2009) while anchovy contributed only ~10,000 metric tons.yr^{-1}. Further north, Pacific Hake and salmonids dominate the higher trophic-level fisheries. The ecosystem supports the foraging and reproductive activities of 2-6 million seabirds from around 100 species [*Briggs and Chu*, 1987]. Marine mammals are diverse and relatively abundant, including recovering populations of Humpback whales, among others [*Barlow et al.*, 2008].

The average temperature of the California Current has warmed by 0.61°C from 1955 to 2005 (1.1, $p < 0.05$, Table 30-2) and from 0.14 to 0.80 ºC (1985-2007, [*Demarcq*, 2009]. Like other EBUEs, the California Current is characterised by large-scale inter-annual and inter-decadal climate-ecosystem variability [*Chavez et al.*, 2003; *Checkley and Barth*, 2009; *Hare and Mantua*, 2000; *McGowan et al.*, 1998]. During an El Niño, coastally-trapped Kelvin waves from the tropics deepen the thermocline, thereby severely reducing upwelling and increasing ocean temperatures from California to Washington [*King et al.*, 2011]. Atmospheric teleconnections to the tropical Pacific alter wind stress and coastal upwelling. Therefore, the ENSO is intimately linked with Bakun's (1990) upwelling intensification hypothesis (Box 30-1). Inter-decadal variability in the California Current stems from variability in the Pacific-North America pattern [*Overland et al.*, 2010], which is influenced by the PDO [*Mantua et al.*, 1997] and the NPGO [*Di Lorenzo et al.*, 2008]. The major effects of the PDO and NPGO appear north of 39°N [*Di Lorenzo et al.*, 2008; *Menge et al.*, 2009].

Increasing upwelling has implications for productivity which is driven primarily by "bottom-up" trophic mechanisms [*Fleeger et al.*, 2006; *Ware and Thomson*, 2005], with upwelling, transport, and chlorophyll concentrations showing strong interannual couplings. These, in turn, influence trophic transfer up the food chain, affecting zooplankton [*Hooff and Peterson*, 2006; *Keister et al.*, 2011], forage fish [*Brodeur et al.*, 2008], seabirds [*Abraham and Sydeman*, 2004; *Ainley et al.*, 1995], and marine mammals [*Barlow et al.*, 2008; *Thompson et al.*, 2012]. Ecosystem dynamics are therefore sensitive to and may be strongly masked or accentuated by natural variability. For instance, the distribution for many species of larval fish in the Californian Current is strongly related to natural variability. However, many species are also moving polewards over long time-spans, an observation which is consistent with observed warming in the region [*Hsieh et al.*, 2009].

There is *robust evidence* that the California Current has experienced a decrease in the number of upwelling events (23-40%) while the duration of each upwelling event has increased such that the overall magnitude of upwelling events has increased from 1967 to 2010 [*Iles et al.*, 2012], which is consistent with changes expected under climate change [*Iles et al.*, 2012]. Oxygen concentrations have also undergone large and consistent decreases from 1984-2006 throughout the California current, with the largest relative decreases occurring below the thermocline (21% at 300 m). The hypoxic boundary layer ($\leq$60 mmol kg^{-1}) has also shoaled up to 90 m in some regions [*Bograd et al.*, 2008]. These changes are consistent with the increased input of organic carbon into deeper layers from enhanced productivity, which stimulates microbial activity and results in the drawdown of oxygen [*Bakun et al.*, 2010]. These changes are likely to reduce the available habitat for key benthic communities as well as fish and other mobile species [*Stramma et al.*, 2012]. Increasing microbial activity will also increase the partial pressure of CO_2, decreasing pH and the carbonate chemistry of seawater. Together with the shoaling of the saturation horizon, these changes have increased the incidence of undersaturated, low pH and corrosive water flowing onto portions of the continental shelf (40-120 m, [*Feely et al.*, 2008] with consequences for industries such as the shellfish aquaculture industry [*Barton et al.*, 2012].

30.5.5.1.4. Humboldt Current

The Humboldt Current is the largest of the four EBUEs, covering an area larger than the other three combined. It comprises the eastern edge of South Pacific Gyre, linking the northern part of the Antarctic Circumpolar Current with the Pacific South Equatorial Current. Although the primary productivity per unit area is modest compared to that of the other EBUEs, the Humboldt Current system has very high levels of fish production. Current catches are in line with a long-term average (since 1960s) of 8 million tons.yr^{-1} (http://www.seaaroundus.org/lme/13/1.aspx) although decadal-scale variations range from 2.5 to 13 million tons.yr^{-1}. While the anchoveta currently contributes 80% of the total catch, they alternate with sardines on a multi-decadal scale, with their dynamics mediated by the approach and retreat of subtropical waters to and from the coast [*Alheit and Bakun*, 2010] in a cycle that does not appear to be due to anthropogenic climate change. Thus, from the late 1970s to early 1990s, sardines were more important [*Chavez et al*., 2003]. The other major commercial fish species are jack mackerel among the pelagic fish, and hake among the demersal fish.

The Humboldt Current has not shown a warming trend in SST over the last 60 years (Table 30-2) which is consistent other data sets (1982-2006, HadISST1.1, [*Belkin*, 2009]; 1985-2007, Pathfinder [*Demarcq*, 2009]. Wind speed has increased in the central portions of the Humboldt Current although wind has decreased in its southern and northern sections (Figure 30-6A, [*Demarcq*, 2009]. The lack of a consistent warming signal may be due to the strong influence of adjacent ENSO activity, which may be exerting opposing drivers on upwelling which (if they intensify) would decrease temperatures.

Primary production is suppressed during warm El-Niño events and amplified during cooler La-Niña phases. These changes affect primary production that propagates through to higher trophic levels [*Chavez et al*., 2003; *Tam et al*., 2008; *Taylor et al*., 2008]. However, in addition to the trophic impacts, there is also a significant thermal impact directly on organisms, which varies depending on thermal adaptation window for each species. A 37-year zooplankton time series for the coast of Peru showed no persistent trend in abundance and diversity [*Ayón et al*., 2004], although observed shifts coincided with the shifts in the regional SST. As for the other EBUEs, there is lack of studies that have rigorously attempted to detect and attribute changes to anthropogenic climate change, although at least one study [*Gutierrez et al*., 2011] provides additional evidence that the northern Humboldt Current has cooled (due to upwelling intensification) since the 1950s, a trend matched by increasing primary production. This is not entirely consistent with the lack of significant change over the period from 1950-2009 (Table 30-2). Nevertheless, these relationships are likely to be complex in their origin, especially in their sensitivity to the long-term changes associated with ENSO and PDO.

30.5.5.2. Key Risks and Vulnerabilities

There is *robust evidence* and *high agreement* that EBUEs are vulnerable to changes that influence the intensity of currents, upwelling and mixing (i.e. SST, wind strength and direction), oxygen content, ocean chemistry, and the supply of organic carbon to deep offshore locations. Extent to which particular EBUEs are vulnerable to these factors depends on their location [*Gruber*, 2011] Figure 3) and other factors such as other sources of nutrient input and fishing pressure [*Bakun et al*., 2010]. This complex interplay between regional and global drivers means that our understanding of how factors such as upwelling within the EBUEs are likely to respond to further climate change is uncertain (Box 30-1).

In the GCM ensembles examined (Table 30-3), modest rates of warming (0.22 – 0.91°C) occur within the four EBUEs, with the differences between the four RCP models examined being minimal in the near term (2010-2039) and range from 0.22ºC to 0.93ºC. By the end of the century, however, EBUE temperatures range from 0.07ºC to 1.02ºC warmer than today under RCP 2.6, and 2.52ºC to 3.51ºC under RCP8.5 (Table 30-4). These high temperatures have the potential to increase stratification of the water column and substantially reduce overall mixing in some areas and sometimes. Contrary to this, is the potential strengthening of coastal wind systems which would intensify upwelling and stimulate primary productivity through the increased injection of nutrients into the photic zone within the EBUEs (Box 30-1). *Garreaud and Falvey* [2009] explored how wind stress along the South

American coast would change by 2100 under B2 and A2 IPCC scenarios. Using an ensemble of 15 coupled atmosphere–ocean Global Circulation Models (GCMs), upwelling favorable southerly wind systems along the subtropical coast of South America increased, extending and strengthening conditions required for upwelling.

Changes in the intensity of upwelling within the EBUEs are *very likley* to drive fundamental changes to the abundance, distribution and viability of their resident biota although their nature and direction is *uncertain*. In some cases, large-scale decreases in primary productivity and dependent fisheries are projected to occur for EBUEs [*Blanchard et al*., 2012] while other projections question the strong connection between primary productivity and fisheries production [*Arístegui et al*., 2009]. Increased upwelling intensity also has potential disadvantages. Elevated primary productivity may lead to decreasing trophic transfer efficiency, thus increasing the amount of organic carbon exported to the seabed (Figure 30-16), where it is *virtually certain* to increase microbial respiration and hence increase oxygen stress [*Bakun et al*., 2010; *Weeks et al*., 2002]. Increased wind stress may also increase turbulence, breaking up food concentrations (affecting trophic transfer), or causing excessive offshore advection, which could remove plankton from shelf habitats.

The central issue for the EBUEs is therefore whether or not upwelling will intensify, and if so, whether the detrimental impacts of upwelling intensification on O_2 and CO_2 will outweigh its benefits to primary production and associated fisheries. These changes need to be considered together with the many other changes that are *likely*. As projected atmospheric CO_2 concentrations increase, upwelling waters will become increasingly corrosive (*very high confidence*). Although there is substantial evidence from other systems that these changes are likely to impact the biota of EBUEs, there are many uncertainties.

30.5.6. Subtropical Gyres

Subtropical gyres (STG) dominate the Pacific, Atlantic and Indian Oceans and consist of large stable water masses that circulate clockwise (northern hemisphere) and anticlockwise (southern hemisphere) due to the Coriolis Effect (Figure 30-1, Figure 30-13A). The oligotrophic areas at the core of the STGs represent one of the largest habitats on Earth, contributing 21.2% of the ocean primary productivity and 8.3% of the global fish catch (Table 30-1). A number of small island nations are found within this region. While many of the observed changes within these nations have been described in previous chapters, region-wide issues and impacts are discussed here given the strong linkages between ocean and coastal issues (e.g. Chapters 5 and 29).

30.5.6.1. Observed Changes and Potential Impacts

The central portions of the STG are oligotrophic (Figure 30-13A). Temperatures within the STGs of the North Pacific (NPAC), South Pacific (SPAC), Indian Ocean (IOCE), North Atlantic (NATL) and South Atlantic (SATL) have increased at rates of 0.024, 0.0236, 0.0322, 0.0248, and 0.0266°C.yr^{-1} from 1998 to 2010 respectively [*Signorini and McClain*, 2012](Figure 30-13B). This is consistent with changes observed from 1955 to 2005 (0.21-0.53ºC, Table 30-2). Salinity has decreased across the North and South Pacific STGs (Figure 30-6D; WGI 3.3.3.1), consistent with warmer sea temperatures and an intensification of the hydrological cycle [*Boyer*, 2005].

It is *very likely* that the tropical gyres in the North and South Pacific have expanded since 1993 (*high confidence*), with these changes being *as likely as not* consequences of changes in wind forcing and long-term variability (WG1 3.6.3). Chlorophyll levels have decreased in NPAC, IOCE and NATL by 9%, 12% and 11%, respectively over and above the inherent seasonal and interannual variability from 1998 to 2010 [*Vantrepotte and Melin*, 2011] Figure 30-13 C). Chlorophyll levels did not change statistically in the remaining two gyres (SPAC and SATL; which has been confirmed for SPAC by [*Lee and McPhaden*, 2010; *Lee et al*., 2010]). Further, over the period 1998-2007, median cell diameter of key species of phytoplankton exhibited statistically significant linear declines of about 2% in the North and South Pacific, and 4% in the North Atlantic Ocean [*Polovina and Woodworth*, 2012]. Changes in chlorophyll and primary productivity in these sub-regions have been noted before [*Gregg et al*., 2005; *Polovina et al*., 2008] and are influenced by seasonal and longer term sources of variability (e.g. ENSO, PDO, 6.3.1, Figure 6-10). These changes represent a significant expansion of the world's most unproductive waters, although caution must be exercised given the limitations of satellite detection methods (6.2, 6.3) and the shortness of records relative to longer-term patterns of climate variability. There is *high confidence* that changes that reduce the vertical transport of nutrients into the euphotic zone (e.g. decreased wind speed, increasing surface temperatures and stratification) will reduce the rate of primary productivity and hence fisheries.

[INSERT FIGURE 30-13 HERE
Figure 30-13: A. Map of SeaWiFS chl-a climatology. The white polygons define the sub-regions that were analyzed and represent the major sub-regions considered as sub-tropical gyres by Signorini and McClain (2012). B. Time series of anomalies in chl-a and B. Sea Surface Temperature SST for STGs in North Pacific (NPAC), South Pacific (SPAC), Indian Ocean (IOCE) North Atlantic (NATL) and South Atlantic (SATL) Oceans.]

30.5.6.1.1. Pacific Ocean STGs

Pacific climate is heavily influenced by the position of the Inter-tropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ), which are part of the ascending branch of the Hadley circulation. These features are also strongly influenced by inter-annual to inter-decadal climate patterns of variability including the ENSO and PDO. The current understanding of how ENSO and PDO are likely to change as average global temperatures increase is *uncertain* [*Collins et al.*, 2010], WG1 12.4.4.2). The position of both ITCZ and SPCZ vary seasonally and with influences such as ENSO [*Lough et al.*, 2011], with a northward migration during the northern hemisphere summer and a southward migration during the southern hemisphere summer. These changes determine the timing and extent of the wet and dry seasons in SPAC and NPAC sub-regions, along with the West Pacific Monsoon [*Ganachaud et al.*, 2011]. Tropical cyclones are prominent in the Pacific (particularly the western Pacific), and CBS sub-regions between 10°-30° north and south of the equator, although the associated storm systems may occasionally reach higher latitudes. Spatial patterns of cyclones vary with ENSO, spreading out from the Coral Sea to the Marquesas Islands during El Niño and contracting back to the Coral Sea, New Caledonia and Vanuatu during La Niña [*Lough et al.*, 2011]. Historically, there has been almost twice as many land falling tropical cyclones during La Niña as opposed to El Niño years off the East coast of Australia, with a declining trend in the number of severe tropical cyclones from 0.45 per year in the early 1870s to 0.17 per year in recent times [*Callaghan and Power*, 2011].

The Pacific Ocean underwent an abrupt shift to warmer sea temperatures in the mid-1970s as a result of both natural (e.g. PDO) and climate forcing [*Meehl et al.*, 2009] (*high confidence*). This change coincided with a similarly sharp change in rainfall observed across the Pacific [*Griffiths et al.*, 2003], especially from 150-180°W. Countries such as the Cook Islands, Tonga, Samoa and American Samoa and Fiji tend to experience drought conditions as the SPCZ (with cooler sea temperatures) moves toward the north-east during El Niño (*moderate confidence*). The opposite is true during La Niña conditions. The impact of changing rainfall on the countries of the Pacific STGs discussed in greater detail elsewhere (5.3.2.5, 5.3.2.6, 29.3.2.2, Table 29-1). While these changes are due to different phases of long-term variability in the Pacific, they illustrate the ramifications and sensitivity of the Pacific to changes in climate change.

Elevated sea temperatures within the Pacific Ocean have increased the frequency of widespread mass coral bleaching and mortality since the early 1980s [*Baker et al.*, 2008; *Donner et al.*, 2010; *Hoegh-Guldberg*, 1999; *Hoegh-Guldberg and Salvat*, 1995; *Mumby et al.*, 2001]. There are few if any scientific records of mass coral bleaching and mortality prior to this period [*Hoegh-Guldberg*, 1999]. Rates of decline in coral cover on coastal coral reef ecosystems range between 0.5 and 2.0% per year depending on the location within the Indo Pacific region [*Bruno and Selig*, 2007; *De'ath et al.*, 2012; *Hughes et al.*, 2011; *Sweatman et al.*, 2011]. The reasons for this decline are complex and involve non-climate change related factors (e.g. coastal pollution, overfishing) as well is global warming and possibly acidification. A recent comprehensive analysis of the impacts of coral bleaching and mortality concluded "that bleaching episodes have resulted in catastrophic loss of coral reefs in some locations, and have changed coral community structure in many others, with a potentially critical influence on the maintenance of biodiversity in the marine tropics" [*Baker et al.*, 2008]. Increasing sea levels have also caused changes in seagrass and mangrove systems. *Gilman et al.* [2007] found a reduction in mangrove area with sea level rise, with the observed mean landward recession of three mangrove areas over four decades being 25, 64, and 72 $mm.yr^{-1}$, 12-37 times faster than the observed rate of sea-level rise. Significant interactions exist between climate change and coastal development, where migration shoreward depends on the extent to which coastlines have been modified or barriers to successful migration have been established.

Reduced ocean productivity of the STGs [*Sarmiento et al.*, 2004; *Signorini and McClain*, 2012] reduces the flow of energy to higher trophic levels, such as those of pelagic fish and sharks [*Le Borgne et al.*, 2011]. The distribution and abundance of fisheries stock such as tuna is also sensitive to changes in sea temperature and hence long-term variability such as ENSO and PDO. The redistribution of tuna in the Western central equatorial region has been related to the position of the oceanic convergence zones, where the warm pool meets the cold tongue of the Pacific. These changes have been reliably reproduced by population models that use temperature as a driver of the distribution and abundance of tuna [*Lehodey et al.*, 1997; *Lehodey et al.*, 2006].

30.5.6.1.2. Indian Ocean STG

Like the Pacific Ocean, the Indian Ocean plays a crucial role in the global weather patterns with teleconnections throughout Africa, Australasia, Asia and the Americas (e.g. [*Clark et al.*, 2000; *Manhique et al.*, 2011; *Meehl and Arblaster*, 2011; *Nakamura et al.*, 2011]. Increasing sea level, temperature, storm distribution and intensity, and changing ocean chemistry set to influence the broad range of physical, chemical and biological aspects of the Indian Ocean. Coral reef ecosystems in the Indian Ocean gyre system were heavily impacted by record positive sea temperature anomalies seen in the southern hemisphere February-April 1998 [*Ateweberhan et al.*, 2011] *robust evidence, high agreement, high confidence*). Coral cover across the Indian Ocean region has declined from 37-39% coral cover in the period 1987 to 1997 to approximately 22% coral cover (1999-2000). Responses to the anomalously hot conditions in 1998 varied between sub-regions, with the central Indian Ocean islands (Maldives, Seychelles, Chagos, and Lakshadweep) experiencing major decreases coral cover from 40 to 53% (1977 to 1997) to 7% (1999-2000) after the 1998 event (*high confidence*, [*Ateweberhan et al.*, 2011]). Coral reefs lining islands in southern India and Sri Lanka experienced similar decreases in coral cover (45% to 13%). Islands in the South West Indian ocean (Comoros, Madagascar, Mauritius, Mayotte, Reunion, and Rodrigues) experienced much lower impacts (44%, 1977-1997 to 40%, 1999-2000). Recovery from these impacts has been variable with sites such as those around the central Indian Ocean islands exhibiting fairly slow recovery (13% by 2001-2005) while those around southern India and Sri Lanka showing much higher rates (achieving a mean coral cover 37% by 2001-2005; [*Ateweberhan et al.*, 2011]. These impacts on key reef-building species are likely to drive major changes in the abundance and composition of fish populations in coastal areas, and affect other ecosystem services that are important for underpinning tourism and coastal protection (Box CC-CR).

Pelagic fisheries that involve tuna and other pelagic species are very valuable to many small island states within the Indian Ocean (Chapter 29). As with Pacific pelagic fisheries, the distribution and abundance of pelagic fisheries in the Indian Ocean is greatly influenced by sea temperature. The anomalously high sea temperatures of 1997-98 (leading to deep mixed layer anomalies) coincided with anomalously low primary production in the Western Indian Ocean and a major shift in tuna stocks within the Indian Ocean [*Menard et al.*, 2007; *Robinson et al.*, 2010], *high confidence*). Fishing grounds in the Western Indian Ocean were deserted and fishing fleets underwent a massive shift toward the eastern basin, which is unprecedented for the tuna fishery. As a result of these changes, many countries throughout the Indian Ocean lost significant tuna related revenue. In the case of the Seychelles in 1998, direct, indirect and induced economic effects of the tuna industry expenditure declined by 58, 26 and 35%, respectively [*Robinson et al.*, 2010]. Observations over the period 1991 to 2007 reveal interactions between depth of the mixed layer and depressed chlorophyll concentrations. In 2007, tuna fishing revenue was again reduced by strong surface warming, the deepening of the mixed layer, and associated with modest reduction in primary productivity. These trends highlight the overall vulnerability of tuna fishing countries to climate change, which is similar for many other countries in the other major oceans of the world.

30.5.6.1.3. Atlantic Ocean STGs

The SST have increased within the STGs of the Atlantic Ocean (Figure 30-13, [*Belkin*, 2009; *Signorini and McClain*, 2012]. The strength of surface winds has also declined over a large portion of the STGs in the Atlantic Ocean (Figure 30-6A, *high confidence*). These changes have influenced the distribution of key fishery species as well the ecology of coral reefs in Bermuda [*Baker et al*., 2008; *Wilkinson and Hodgson*, 1999] and in the eastern Caribbean [*Eakin et al*., 2010]. Small island nations such as Bermuda depend on coral reefs for fisheries and tourism and are vulnerable to further increases in sea temperature that cause mass coral bleaching and mortality (Box CC-CR; Figure 30-12). As with the other STGs, phytoplankton communities and pelagic fish stocks are sensitive to temperature changes that have occurred over the past several decades. Observations to the changes have enabled models to be developed which have a high degree of accuracy in projecting the distribution and abundance of these elements within the Atlantic region generally [*Cheung et al*., 2011].

30.5.6.2. Key Risks and Vulnerabilities

The vast STGs of the Atlantic, Pacific and Indian oceans are responsive to increasing temperature which is *very likely* to increase water column stratification which is *likely* to reduce surface concentrations of nutrients, and consequently, primary productivity (*medium confidence*). Warming is projected to continue (Table 30-4), with substantial increases in the risk and vulnerability associated with systems that have been observed to change so far (*high confidence*; Figure 30-12). Under RCP2.6, the temperatures of the STGs are likely to increase by 0.20-0.55°C warmer in the near term (2010-2039) and between 0.00-0.87°C by the end of the century (Table 30-4). Under RCP8.5, however, surface temperatures of the world’s STGs are projected to be 0.49-0.90°C warmer in the near term (2010-2039) and 2.05-3.44°C warmer by the end of the century (Table 30-4). These changes in temperature are *very likely* to increase water column stability, reduce the depth of the mixed layer, and influence key parameters such as nutrient availability and oxygen concentrations. It is *uncertain* how longer term sources of variability such as ENSO and PDO will change and ultimately influence these trends.

The world's most oligotrophic ocean sub-regions will continue to expand over coming decades with consequences for ecosystem services such as gas exchange, fisheries and carbon sequestration if a large part of recent changes have an origin in climate change. *Polovina et al*. [2011] explored this question for the North Pacific using a climate model that included a coupled ocean biogeochemical component to investigate potential changes under an SRES A2 scenario (~RCP 6.0 – 8.5). Model projections demonstrated that the STG expanded by approximately 30% by 2100, driven by the northward drift of the mid-latitude westerlies and enhanced stratification of the water column. The expansion of the STG occurred at the expense of the equatorial upwelling and other regions within the North Pacific. The total primary production and fish catch of the new enlarged STG is projected to increase by 26% although primary production per area declined slightly [*Polovina et al*., 2011].

Understanding how storm frequency and intensity is likely to change represents a significant question for many countries within the STGs. Projections of increasing sea temperature are *likely* to change the behavior of tropical cyclones. At the same time, the maximum wind speed and rainfall associated with cyclones is *likely* to increase, although future trends in cyclones and severe storms are *very likely* to vary from region to region (WG1 Box 14.2). Patterns such as “temporal clustering” can have a strong influence on the impact of tropical cyclones on ecosystems such as coral reefs [*Mumby et al*., 2011], although how these patterns are likely to change within the STG is uncertain at this point. There is, however, *medium to high confidence* that an intensifying hydrological cycle is likely to increase precipitation in many areas (WG1 2.6.3, 14.2.5), although longer droughts are also expected in other STGs (*medium confidence*). Improving our understanding of how weather systems associated with features such as the South Pacific Convergence Zone (14.3.1.2) are likely to vary is critical to climate change adaptation of a large number of nations associated with the STGs. Developing an understanding of how water temperature, climate systems such as SPCZ and ITCZ, climate change, and long-term cycles such as ENSO interact will be essential in this regard.

The impacts of projected sea temperatures on the frequency of coral bleaching and mortality within two key sub-regions within the STG are outlined in Box CC-CR and Figure 30-12. As with other sub-regions dominated by coral reefs, mass coral bleaching and mortality becomes an annual risk under all scenarios, with mass mortality events beginning to occur every 1-2 years by 2100 (Box CC-CR, Figure 30-12). Coral dominated reef ecosystems (areas with more than 30% coral cover) are *very likely* disappear under these circumstances by the mid to late part of this century [*Bell et al*., 2013a; *Donner et al*., 2005; *Dove et al*., 2013; *Frieler et al*., 2012]. The loss of substantial coral communities has implications for the three-dimensional structure of coral reefs (Figure 30-12; Box CC-CR), and the role of the latter as habitat for organisms such as fish [*Bell et al*., 2013a; *Hoegh-Guldberg*, 2011; *Hoegh-Guldberg et al*., 2011b; *Pratchett et al*., 2011a]. The impacts of increasing sea temperature can be exacerbated by increasing ocean acidification with potential impacts on calcification [*Doney et al*., 2009; *Hoegh-Guldberg et al*., 2007; *Kleypas et al*., 1999] *medium confidence*), reef metabolism and community calcification [*Dove et al*., 2013], and other key ecological processes [*Munday et al*., 2009; *Portner et al*., 2007; *Portner et al*., 2001], 6.2.2.4.4). Ocean pH within the STGs will continue to decrease as atmospheric carbon dioxide increases, bringing pH within the STGs to 7.7 (800 ppm) and 7.9 (450 ppm, Figure 30-7A; Box CC-OA). Aragonite saturation states will decrease to around 1.6 (800 ppm,) and 3.3 (450 ppm, Figure 30-7B). Decreasing carbonate ion situations and saturation states pose serious risks to other marine calcifiers such as encrusting coralline algae, coccolithophores, and a range of invertebrates [*Doney et al*., 2009; *Feely et al*., 2009]. Increasing sea temperatures and sea level are also likely to influence other coastal ecosystems (e.g. mangroves, seagrass meadows) in the Pacific although significant gaps and uncertainties exist (6.4.1.2.2, 29.3.1.4, [*Waycott et al*., 2007]. There is *medium confidence* that many of the negative consequences for coral reefs, mangroves and seagrass meadows are *likely* to have negative consequences for dependent coastal fisheries (through destruction of habitat) and tourism industries [*Bell et al*., 2011; *Pratchett et al*., 2011a; *Pratchett et al*., 2011b]Table 29.3, WGII Ch29, *medium confidence*).

Changes to sea temperature also lead to changes in the distribution of key pelagic fisheries such as Skipjack Tuna (*Katsuwonus pelamis*), Yellowfin Tuna (*Thunnus albacares*), Big-eye Tuna (*T. obesus*) and South Pacific Albacore Tuna (*T. alalunga*), which make up the majority of key fisheries in the Pacific Ocean. Changes in the distribution and recruitment in response to changes in sea temperature as result of ENSO demonstrate a close association of pelagic fish stocks and water temperature. As a result, populations of key pelagic fishery species are projected to move many hundreds of km east from where they are today [*Lehodey et al*., 2008; *Lehodey et al*., 2010; *Lehodey et al*., 2011], *high confidence*) with implications for income, industry and food security across multiple Pacific Island nations [*Bell et al*., 2011; *Cheung et al*., 2010; *McIlgorm et al*., 2010], 7.4.2.1, Table 29.2:, Table 29.3, *high confidence*). Our understanding of the impacts of reduced oxygen on pelagic fish populations is uncertain although there is a *high agreement* on the potential physiological impacts (6.3.3). Those species that are intolerant to hypoxia, such as tuna, will have their depth range compressed, which may reduce their vulnerability to being caught (positively) and overall fisheries habitat and productivity (negatively, [*Stramma et al*., 2010; *Stramma et al*., 2011]; *high confidence*). Despite the importance of these potential changes, our understanding of the full range of impacts is limited at this point.

The shift in habitat for top predators in the Pacific was examined by *Hazen et al*. [2012] who used tracking data from 23 marine species and associated environmental variables to predict increases and decreases of up to 35% in core habitat for many species within the Pacific. Potential habitat contracted for Blue Whales, Salmon Sharks, Loggerhead Turtles, Blue Shark and Make Sharks, while potential habitat expanded for Sooty Shearwaters, Black Footed Albatross, Leatherback Turtles, White Sharks, Elephant Seals, Albacore, Bluefin and Yellowfin Tuna [*Hazen et al*., 2012]. These directional changes represents an opportunity to participate and apply anticipate change and to apply large-scale management strategies to preserve these valuable species.

30.5.7. Deep Sea (>1000 m)

Assessments of the influence of climate change on the deep sea are challenging due to difficulty of access and scarcity of long-term, comprehensive observations [*Smith et al*., 2009]. The size of this habitat is also vast, covering well over 60% of the earth's surface and stretching from top of the mid-oceanic ridges to bottom of deep ocean trenches. The fossil record in marine sediments reveals that the deep ocean environment has undergone large changes due to climate change in the past [*Knoll and Fischer*, 2011]. The paleo-skeletal record shows it is the rate, not simply magnitude, of climate change (temperature, oxygen and carbon dioxide) that is critical to marine life. The rate of change today in key parameters *very likely* exceeds that of other major events in Earth history. Two primary time scales are of interest. The first is the slow rate (century scale) of ocean circulation and mixing and consequently the slow rate at which deep-sea ecosystems experience physical climate change. The second is the rapid rate at which organic matter enters the deep ocean from primary productivity generated at surface of the ocean, which represents a critical food supply to deep-sea animals [*Smith et al.*, 2009; *Smith et al.*, 2008]. Since the upper ocean is currently experiencing warming, increased stratification, and changing productivity (WG1 3.2.2) there is evidence (*medium confidence*) of impacts on quite different time scales between the slow warming at depth and the more rapidly changing (decreasing/increasing) food supply to deep-sea animals that falls from above.

30.5.7.1. Observed Changes and Potential Impacts

The greatest rate of change of temperature is occurring in the upper 700 m of the ocean (WG 1 3.2, *very high confidence*), although smaller yet significant changes are occurring at depth. The deep-sea environment is typically cold (~ 1-4°C) although abyssal temperatures in SES can be higher (e.g. Mediterranean ~12°C, Red Sea ~22°C). In the latter case, deep-sea populations can thrive in these environments as well, illustrating the variety of temperature conditions that differing species of abyssal life have adapted to. Individual species, however, are typically constrained within a narrow thermal and oxygen-demand window of tolerance [*Portner*, 2010] and therefore it is *very likely* that major shifts in the distribution of deep-sea species will occur. Warming over multiple decades has been observed below 700 m [*Levitus et al.*, 2005; *Levitus et al.*, 2009], with warming being minimal at mid-range depths (2000-3000 m), and increasing towards the sea floor in some sub-regions (e.g. Southern Ocean) (WGI Ch3). For the deep Atlantic Ocean, the mean age of deep-waters (mean time since last exposure to the atmosphere) is ~250 years; the oldest deep waters of the Pacific Ocean are >1,000 years old. The patterns of ocean circulation are clearly revealed by the penetration of tracers and the fossil-fuel CO_2 signal itself into the abyss [*Sabine et al.*, 2004]; the time scale for full equilibration of deep ocean waters and their ecosystems with modern warming and CO_2 levels is many centuries [*Wunsch and Heimbach*, 2008].

Temperature accounts for ~86% of the variance in the export of organic matter to the deep sea (*moderate confidence*)[*Laws et al.*, 2000]. Consequently, upper-ocean warming will (*medium confidence*) reduce the export of organic matter to the deep sea, impacting the distribution and abundance of deep sea organisms and associated food webs and ecosystem processes [*Smith Jr and Kaufmann*, 1999; *Smith et al.*, 2008]. Most organic matter entering the deep ocean is recycled by microbial systems at relatively shallow depths [*Buesseler et al.*, 2007], at rates which are temperature dependent. Upper ocean warming will increase the rate of sub-surface decomposition of organic matter (*high confidence)*, thus intensifying the intermediate depth oxygen-minimum zones [*Stramma et al.*, 2008; *Stramma et al.*, 2010] and reducing food supply to the abyssal ocean.

Quantifying these effects is difficult since complex ecosystem responses are likely and information is sparse. Food supply to depths below the euphotic zone is about 20% of net primary productivity. The vast majority of this is recycled by microbes at depths shallower than 1,000. The net result is that with warming of the upper ocean food supply to the deep sea will decrease. If the temperature dependence assumed by models such as that of *Laws et al.* [2000] is correct, then warming of the ocean basins by 2.5ºC (Table 30-4) would reduce the fraction exported to the deep sea by about 5%. Warming of intermediate waters will increase respiration at mid-water depths. The temperature dependence of mid-water respiration rates is not well known, but is *likely* (*moderate confidence*) to be similar to microbial rates in environments such as soils and sediments with a Q_{10} of about 2.5 [*Thamdrup et al.*, 1998]. This suggests that a reduction in food supply to the deep sea from 20% to 16% of global net primary production (7.2 Gt C yr-1) could occur (medium confidence) under a 2.5ºC warming of the upper ocean. The impacts of climate change on other deep sea communities such as hydrothermal vent ecosystems are unknown [*Van Dover*, 2012].

The oxygen concentrations of the deep areas of the Ocean are decreasing [*Helm et al.*, 2011b; *Karstensen et al.*, 2008; *Keeling et al.*, 2010; *Stramma et al.*, 2008]. The largest signals occur at intermediate water depths shallower than 1,000 m [*Nakanowatari et al.*, 2007; *Whitney et al.*, 2007], but some waters >1,000 m depth are also experiencing decline [*Falkowski et al.*, 2011; *Jenkins*, 2008]. The quantity of dissolved oxygen will be reduced with ocean warming due to direct effects on solubility (*high confidence*) with these effects being widely distributed [Shaffer et al. 2009]. It is also *virtually certain* that metabolic rates of all animals and microbial respiration rates will increase with temperature [*Brown et al.*, 2004]. Thus, increased microbial activity and reduced oxygen solubility at higher temperatures will have additive impacts on the decline of oxygen (*high confidence*). Deep-sea waters have relatively high pO_2 due to the thermodynamic effects of pressure, and also from low microbial consumption rates associated with the small supply of organic matter. Oxygen concentrations will be less well oxygenated at mid depths as compared to deepest sites within the ocean which experience the highest pO_2 on Earth due to the very high pressures *(very high confidence).*

Increasing deep water under-saturation for calcite and aragonite will impact carbonate shell formation and dissolution as has happened many times in Earth's past ([*Zeebe and Ridgwell*, 2011](*high confidence).* Some cold-water deep-sea corals (reported down to 3,500m) already exist in waters under-saturated with respect to aragonite [*Lundsten et al.*, 2009]. These corals will face reduced calcification and growth rates from decreased food supply and altered seawater carbonate concentrations and pH (*high confidence*) [*Guinotte et al.*, 2006].

30.5.7.2. Key Risks and Vulnerabilities

Rising atmospheric CO_2 poses a risk to deep-water communities through increasing temperature, and decreasing oxygen, carbonate chemistry, and pH (*high confidence*). The resulting changes to the flow of organic carbon to some parts of the deep ocean (e.g. STGs) are very likely to impact deep-ocean ecosystems (*medium confidence*). Changes in temperature and the supply of organic carbon from surface waters are likely to interact and increase the risk of impacts to deep-ocean ecosystems. Changes in temperature, oxygen, and CO_2 may also increase the vulnerability of the daily vertical migration of mid-water populations. As with the deep sea generally, there is a need to fill in the substantial gaps that exist in our knowledge and understanding of the world's largest habitat and its responses to rapid anthropogenic climate change.

30.5.8. Detection and Attribution of Climate Change Impacts with Confidence Levels

The preceding analysis has identified a wide range of physical, chemical and ecological components that have changes over the decades and the last century. In some cases, confidence in both the detection and attribution of the changes to climate change is high. In other cases, confidence varies in both elements leading to lower levels of certainty surrounding whether or not specific changes can be attributed to anthropogenic climate change. Figure 30-14 summarises a number of examples from the Ocean as a region together with the degree of confidence in the detection and attribution steps. Physical and chemical changes such as ocean warming and acidification, confidence is extremely high that changes are being detected and they are due to climate change. Several ecological responses also fall in the upper corner such as changes in the distribution of marine plants and animals, and with respect to climate change driving more intense and frequent mass coral bleaching and mortality events. Other areas are of lower confidence, either because the detection of changes has been difficult (e.g. field evidence of declining calcification) yet models are in strong agreement that there should be a relationship, or where confidence is high when it comes to detection yet our models are in conflict (e.g. wind-driven upwelling). This analysis is further explored in Ch18.

[INSERT FIGURE 30-14 HERE
Figure 30-14: Expert assessment of degree of confidence in detection and attribution across sub-regions and processes (based on evidence explored throughout Chapter 30).]

30.6. Sectoral Impacts, Adaptation, and Mitigation Responses

The Ocean supports numerous sectors, many of which have been discussed in previous regional chapters of this assessment. Discussion here is restricted to economic, environmental and social sectors that have a direct relevance to the Ocean such as fisheries, tourism, shipping, oil and gas, maritime security, and renewable energy, as well as sectors that have significant non-market values such as ecosystem goods and services. The impacts of climate change on ocean sectors will be mediated through simultaneous changes in multiple environmental and ecological variables (Figure 30-15). Many climate change impacts can be avoided, reduced or delayed by mitigation, yet both short-term and longer-term adaptation are necessary to address impacts that result from warming, even under the lowest stabilization scenarios assessed.

[INSERT FIGURE 30-15 HERE
Figure 30-15: A. Summary of regional impacts and opportunities associated with climate change on the world's ocean region. B. Example of changes occurring within fisheries across the Ocean.]

Sectoral approaches dominate resource management in the Ocean (i.e. shipping tends to be treated in isolation from fishing within an area), yet cumulative and interactive effects of individual stressors are known to be ubiquitous and substantial [*Crain et al.*, 2008]. Climate change consistently emerges as a dominant stressor in regional to global-scale assessments [*Halpern and Floeter*, 2008; *Halpern et al.*, 2010; *Halpern et al.*, 2009a; *Halpern et al.*, 2009b; *Halpern et al.*, 2009c; *Selkoe et al.*, 2009], but land-based pollution, commercial fishing, invasive species, and commercial activities such as shipping all rank high in many places around the world, especially coastal waters [*Halpern et al.*, 2010; *Halpern et al.*, 2009a]. Such cumulative effects pose challenges to managing for the full suite of stressors to marine systems, but also present opportunities where mitigating a few key stressors can potentially dramatically improve overall ecosystem condition (e.g.[*Halpern et al.*, 2010]). The latter has often been seen as a potential strategy for reducing climate impacts on marine ecosystems by increasing ecosystem resilience, thus buying time while the core issue of reducing greenhouse gas emissions is tackled [*Hughes et al.*, 2003].

30.6.1. Natural Ecosystem Services

Human welfare is highly dependent on ecosystem services provided by the Ocean. Many of these services are provided from coastal and shelf areas, and are consequently addressed in other chapters. Oceans contribute provisioning (e.g. food, raw materials; see 30.6.3.1), regulating (e.g. gas exchange, nutrient recycling, carbon storage, climate regulation, water flux), supporting (e.g. habitat, genetic diversity) and cultural (e.g. recreational, spiritual) services [Millennium Ecosystem Assessment, 2005]. The accumulating evidence fundamental ecosystem services within the ocean are shifting rapidly should be of major concern, especially with respect to the ability of regulating and supporting ecosystem services to underpin current and future human population demands [Rockstrom et al., 2009].

Supporting, regulating and cultural ecosystem services tend to transcend the immediate demands placed on provisioning services, and are difficult to value in formal economic terms due to their complexity, problems such as double counting and the value of non-market goods and services arising from marine ecosystems generally [*Beaudoin and Pendleton*, 2012; *Fu et al.*, 2011]. Pursuing a formal valuation of ecological services from the Ocean, however, has the potential to provide adaptation options for stimulating more effective governance, regulation and ocean policy while at the same time potentially improving the management of these often vulnerable services through the development of market mechanisms and incentives [*Beaudoin and Pendleton*, 2012]. Other strategies have involved placing larger areas of the ocean under management in order to protect and maintain the health and function of ocean ecosystems [*Agardy et al.*, 2011; *Edgar*, 2011; *Game et al.*, 2009]. The planetary scale changes that are currently occurring, however, require concerted international action on the fundamental drivers of change (anthropogenic greenhouse gas emissions) otherwise many of the proposed adaptation options will fail.

Adaptation strategies that reduce the impact of climate change on ocean ecosystems and their services include managing local factors not related to climate change. Overfishing, pollution, deteriorating water quality, and habitat loss often interact with climate change to produce greater effects than if each were to occur on their own (i.e. producing synergistic interactions). Coral reefs, for example, will recover three times faster from mass coral bleaching and mortality if healthy populations of herbivorous fish are maintained [*Hughes et al.*, 2003], indicating that controlling overfishing will help maintain coral-dominated reef systems while the international community reduces the emissions of greenhouse gases and stabilises global temperature. In a similar way, 'Blue carbon' provides opportunities for mitigation and by extension to other ecosystems services, adaptation. Blue carbon is defined as the organic carbon trapped and stored within marine ecosystems such as phytoplankton, mangrove, seagrass and salt marsh ecosystems. Destroying and removing these ecosystems exposes organic carbon to the atmosphere, leading to the oxidation and release into the atmosphere. Combining data on global area, land-use conversion rates and near surface carbon stocks for marshes, mangroves and seagrass meadows, *Pendleton et al.* [2012] revealed that the destruction of these three ecosystems was equivalent to 3-19% of the emissions generated by deforestation globally with economic damages estimated to be US$6-42 billion annually. In driving the preservation of coastal ecosystems, strategies involving Blue Carbon and other strategies can also enhance adaptation against sea level rise and storm damage, as well as maintaining habitat for fisheries species. The current understanding of Blue Carbon is uncertain given limited knowledge, methodologies and policies for measuring and implementing blue carbon strategies.

30.6.2. Economic Sectors

30.6.2.1. Fisheries

Capture fisheries and aquaculture supplied the world with 148 million tonnes of fish and shellfish in 2010. This production was valued at US$217.5 billion, and supplied 18.8 kg of protein-rich food per person in 2011 [*FAO*, 2012]. The world's oceans provided 64% of the total world fisheries in 2011. Production from marine aquaculture increased from 16 million tonnes in 2006 to 18 million tonnes in 2010 whereas marine capture fisheries declined over the same period from 80 to 77 million tonnes per year [*FAO*, 2012]. The significance of marine capture fisheries is also illustrated powerfully by the number of people engaged in small-scale marine fisheries in developing countries. These small-scale fisheries account for 28 million of the ~80 million tonnes of fish caught from the ocean, and provide jobs for more than 47 million people – about 12.5 million fishers and another 34.5 million people engaged in post-harvest activities [*Mills et al.*, 2011].

The stagnation of marine capture fisheries production is attributed to full exploitation of 60% of the world's fisheries, and overexploitation of another 30% of fisheries [FAO, 2012]. The main problems with industrial fisheries include illegal, unreported and unregulated fishing; ineffective implementation of monitoring, control and surveillance and overcapacity in fishing fleets [*World Bank/FAO,* 2008; *FAO*, 2012].]. Such problems are being progressively addressed in several developed and developing countries [*Hilborn;* 2007; *Worm et al.,* 2009][*Pitcher et al.*, 2009], where investments have been made in stock assessment, strong management and application of the FAO Code of Conduct for Responsible Fisheries and the FAO Ecosystem Approach to Fisheries Management.

A different governance approach is needed in most cases for small-scale fisheries, which are often characterised by large numbers of politically weak fishers operating from decentralized localities, poor governance and insufficient data to monitor catches effectively [*Kurien and Willmann*, 2009; *Cochrane et al.* 2011; *Pomeroy and Andrew*, 2011]. For these fisheries, management that aims to avoid further depletion of overfished stocks is likely to be more appropriate in the short term than management aimed at maximising sustainable production. These aims can be achieved through (1) 'primary fisheries management', which uses simple harvest controls (e.g. size limits, closed seasons and areas, gear restrictions and protection of spawning aggregations) to avoid irreversible damage to stocks in the face of uncertainty [*Cochrane et al.* 2011], and (2) investing in the social capital and institutions needed for communities and governments to manage small-scale marine fisheries [*Hall et al.*, 2013; *Pomeroy and Andrew*, 2011].

Changes to sea temperature and other factors as a result of anthropogenic climate change is generating new challenges for fisheries as coastal and oceanic environments experience the loss of habitat, the spread of disease and invading species, and changes in the availability of food. There is *medium evidence* and *robust agreement* that these changes will change both the nature of fisheries and their ability to provide food and protein for hundreds of millions of people. These risks for ecosystems and fisheries vary from region to region (Figure 30-15, Chapter 7), with potential increases in fisheries production over the short term at high latitudes, and potential decreases at lower latitudes.

The challenges of optimising the economic and social benefits of both industrial and small-scale marine fisheries, which already include strategies to adapt to climatic variability [*Salinger et al.*, 2013], are now made more complex by climate change [*Cochrane et al.*, 2009; *Brander*, 2010; 2013]. Nevertheless, vulnerability assessments have identified practical adaptations to assist enterprises, communities and households to reduce the risks from climate change and capitalise on the opportunities. The diversity of these adaptation options, and the policies needed to support them, are illustrated by the following examples.

30.6.2.1.1. Tropical fisheries based on top predators

Fisheries for Skipjack, Yellowfin, Big-eye and Albacore Tuna provide substantial economic and social benefits to the people of Small Island Developing States (SIDS). For example, tuna fishing license fees contribute substantially (up to 40%) to the government revenue of several Pacific Island nations [*Gillett*, 2009; *Bell et al.,* 2013b]. Tuna fishing and processing operations also contribute up to 25% of gross domestic product in some of these nations and employ over 12,000 people [*Gillett*, 2009; *Bell et al.*, 2013b]. Considerable economic benefits are also derived from fisheries for top pelagic predators in the Indian and Atlantic oceans [*Bell et al.*, 2013b; *FAO*, 2012]. Increasing sea temperatures and changing patterns of upwelling are projected to cause shifts in the distribution and abundance of pelagic top predator fish stocks (30.5.4, 30.5.5), with potential to create 'winners' and 'losers' among island economies as catches of the trans-boundary tuna stocks change within their exclusive economic zones [*Bell et al.*, 2013b].

A number of practical adaptation options and supporting policies to minimize the risks and maximize the opportunities associated with the projected changes in distribution of the abundant Skipjack Tuna in the tropical Pacific have been identified [*Bell et al.*, 2011; *Bell et al.*, 2013a](Table 30-5). These adaptation and policy options include: (1) full implementation of the regional 'vessel day scheme' designed to distribute the economic benefits from the resource in the face of climatic variability, and other schemes to control fishing effort in subtropical areas; (2) strategies for diversifying the supply of fish for canneries in the west of the region as tuna move progressively east; (3) continued effective fisheries management of all tuna species; (4) energy efficiency programs to assist domestic fleets to cope with increasing fuel costs and the possible need to fish further from port; (5) the eventual restructuring of regional fisheries management organizations to help coordinate management measures across the entire tropical Pacific; and (6) provision of operational-level catch and effort data from all industrial fishing operations to improve models for projecting redistribution of tuna stocks during climate change [*Salinger et al.* 2013].

[INSERT TABLE 30-5 HERE
Table 30-5: Examples of priority adaptation options and supporting policies to assist Pacific Island countries and territories to minimize the threats of climate change to the socio-economic benefits derived from fisheries and aquaculture, and to maximize the opportunities. These measures are classified as 'win-win' (W-W) adaptations, which address other drivers of the sector in the short term and climate change in the long term, or 'lose-win' (L-W) adaptations, where benefits exceed costs in the short term but accrue under longer-term climate change (Modified from *Bell et al.* 2013a).]

Other adaptation options and policies have been recommended to increase access to tuna caught by industrial fleets for people in rapidly-growing urban centers. These options center on amending licensing conditions to ensure that sufficient high-quality tuna and by-catch are landed locally to provide the large quantities of fish needed for food security in Pacific Island nations [*Bell et al.*, 2011; *Bell et al.,* 2013a]. Similar adaptation options and policy responses are expected to be relevant to the challenges faced by tuna fisheries in the tropical and subtropical Indian and Atlantic oceans.

30.6.2.1.2. Coral reef fisheries

Coral reefs provide habitats for a wide range of harvested fish and invertebrate species. Despite their importance to many developing countries, these ecosystems are under serious pressure from human activities that include deteriorating coastal water quality, sedimentation, ocean warming and acidification (30.3, 30.5, 7.2.13, Box CC-CR). These pressures are translating into a steady decline in live coral cover which is very likely to continue over the coming decades, even where integrated coastal zone management is practiced well. For example, coral losses around

Pacific Islands are projected to be as high as 75% by 2050 [*Bell et al.*, 2013a]. Even under the most optimistic projections (a 50% loss of coral by 2050), changes to state of coral reefs (Box CC-CR; Figure 30-12) are *very likely* to reduce the availability of associated fish and invertebrates that support many of the coastal fisheries in the tropics (*high confidence*). In the Pacific, the productivity of coral reef fisheries has been projected to decrease by at least 20% by 2050, which is also likely to occur in other coral reef areas globally given the similar and growing amounts of stress in these other regions (Table 30-2, 30.4). Other economic activities based on coral reef species, e.g. pearl farming, may also be impacted by changing sea temperature and ocean chemistry. Survival and growth of wild spat used to supply the pearl oysters for farms in Polynesia could decline as shells are weakened by lower aragonite concentrations [*Bell et al.*, 2011]. Reduced availability of aragonite may also affect pearl quality [*Welladsen et al.*, 2010].

Adaptation options and policies for building the resilience of coral reef fisheries to climate change suggested for the tropical Pacific include: (1) strengthening the management of catchment vegetation to improve water quality along coastlines: (2) reducing direct damage to coral reefs; (3) maintaining connectivity of coral reefs with mangrove and seagrass habitats; (4) sustaining and diversifying the catch of coral reef fish to maintain their replenishment potential; and (5) transferring fishing effort from coral reefs to near-shore Skipjack and Yellowfin Tuna resources by installing anchored fish aggregating devices close to shore [*Bell et al.*, 2011, 2013a] (Table 30-5). These adaptation options and policies represent a ‘no regrets’ strategy in that they provide benefits for coral reef fisheries and fishers irrespective of the impacts of climate change.

30.6.2.1.3. Northern Hemisphere HLSBS fisheries

The high latitude fisheries in the northern hemisphere span from around 30/35 ºN to 60ºN in the North Pacific and 80 ºN in the North Atlantic covering a wide range of thermal habitats from subtropical/temperate species to boreal/arctic species. The characteristics of these HLSBS environments as well as warming trends are outlined in 30.5.1 and Table 30-4. As a result of 30-years increase in temperature (Table 30-2; [*Belkin*, 2009; *Sherman et al.*, 2009], there has been a boost in fish stocks in high latitude fisheries in the northern hemisphere, particularly in the Norwegian spring-spawning herring which recovered from nearly extinction caused by a combination overfishing and cooler climate during the 1960s [*Toresen and Østvedt*, 2000]. The major part of high-latitude fish stocks, pelagic as well as demersal, are boreal species located north of 50ºN. Climate change is projected to increase high latitude plankton production and displace zooplankton and fish species poleward. As a combined result of these changes future, the abundance of fish (particularly boreal species) may increase in the northernmost part of the high latitude region [*Cheung et al.*, 2011] although moderately in some regions.

Both demersal and pelagic fish have shown considerable variation in abundance and distribution with climate fluctuation and climate change, but the changes in distribution and migration of the pelagic fishes are considerably larger. These changes have increased tensions leading to what many consider the first climate change related conflicts between fishing nations (30.6.5), which has emphasized the importance of developing international collaboration and frameworks for decision making (30.6.7, 15.4.3.3). The Atlantic mackerel has been a shared stock between EU and Norway due to its newer historical distribution. The recent advancement of the Atlantic mackerel into the Icelandic EEZ during summer has resulted in fishing from Iceland outside internationally agreed fishing quotas. Earlier records of mackerel during first half of 20th and second half of 19th century show, however, that mackerel has been present in Icelandic waters also in the earlier warming periods [*Astthorsson et al.*, 2012]. In the Barents Sea, the Northeast Arctic cod reached record-high abundance during 2012 and also reached its northernmost distribution, 82 ºN, ever recorded. A further northward migration is impossible since this would be into the deep-sea Polar Basin beyond the habitat of shelf species. A further advancement eastwards on the Siberian shelf is, however, possible. The Northeast Arctic cod is shared exclusively by Norway and Russia. Up to now there has been a good agreement between those two nations on the management of the stock.

The HLSB fisheries make up a large-scale high-tech industry with large investments in highly mobile fishing vessels, equipment and land-based industries. Knowledge on how climate fluctuations and change impacts growth, recruitment and distributions in fish stocks is presently not utilized in management strategies for fisheries. These strategies are vital for fisheries that hope to cope with the challenges of a changing ocean environment, and are centrally important for any attempt to develop ecosystem-based management and sustainable fisheries under climate change. The large pelagic stocks with their climate-dependent migration pattern are shared among several nations. Developing equitable sharing of fish quotas is a needed adaption for a sustainable fishery. Factors presently taken into account in determining the shares of quotas are the historical fishery, bilateral exchanges of quotas for various species, and occupation time of the stocks in the various EEZs. Some of the problems and options are discussed further in 30.6.7.

30.6.2.2. Tourism

Tourism recreation represents one of the world's largest industries, accounting for 9% (> US$6 trillion) of global GDP and employing over 255 million people. A large proportion of tourism occurs within coastal and marine settings. It is expected to grow by an average of 4% annually and reach 10% of global GDP within the next 10 years [*WTTC*, 2012]. As with all tourism, that which is associated with the ocean is heavily influenced by climate change, global economic and socio-political conditions, and their interactions [*Scott et al.*, 2012a]. Climate change by impacting ecosystems negatively (e.g. coral reefs) is reducing destination appeal, increasing operating costs and bringing increased uncertainty into a highly sensitive business environment [*Scott et al.*, 2012a].

Several facets of the influence of climate change on the Ocean directly impact tourism. Sea level rise through its influence on coastal erosion and submergence, salinization of water supplies, and changes to storm surge increase the vulnerability of coastal tourism infrastructure, tourist safety and iconic ecosystems (*high confidence*, 30.3.1.2, 5.3.2.4, [*IPCC*, 2012],Table SPM.1). Approximately 29% resorts in the Caribbean are within 1 m of the high tide mark, with 60% being at risk of beach erosion from rapid sea level rise [*Scott et al.*, 2012b]. Extreme events such as violent storms, long periods of drought, and/or extreme precipitation events can decrease the attractiveness and reputation of tourist destinations (5.3.2.4, [*IPCC*, 2012]).

Increasing sea temperatures (30.3.1.1) through their influence on the movement of organisms and the health of ecosystems such as coral reefs can change the attractiveness of locations and the opportunities for tourism (Box CC-CR, [*UNWTO and UNEP*, 2008]. Mass coral bleaching and mortality (triggered by elevated sea temperatures) also has the potential to decrease the appeal of diving related tourism, although the awareness by tourists (e.g. < 50% of tourists were concerned about coral bleaching during 1998) and expected economic impacts has been found to be uncertain [*Scott et al.*, 2012a]. Some studies, however, have picked up reduced tourists satisfaction and the identification of 'dead coral' being one of the reasons for disappointment at the end of the holiday [*Westmacott et al.*, 2001]. Other forms of nature-based tourism are also vulnerable to climate change. For example, the whale watching businesses ($1 billion worldwide in 2001) will be affected by climate change impacts on whale distributions, abundance, and species composition [*Lambert et al.*, 2010]. Anticipated changes include a decline of deep-water whale species diversity in the tropics and increases at higher latitudes [*Whitehead et al.*, 2008].

Tourists respond to changes in factors such as weather and opportunity by expressing different preferences. For example, preferred conditions and hence tourism are projected to shift towards higher latitudes with climate change, or from summer to cooler seasons [*Amelung et al.*, 2007]. Options for adaptation by the marine tourism sector include: (1) identifying and responding to inundation risks with current infrastructure, and planning for projected sea level rise when building new tourism infrastructure (5.6; Scott et al. 2012); (2) promote shoreline stability and natural barriers by preserving ecosystems such as mangroves, salt marsh and coral reefs (5.6, Scott 2012); (3) deploying forecasting and early warning systems in order to anticipate challenges to the structure, appeal, and visitors [*IPCC*, 2012; *Strong et al.*, 2011]; (4) preparation of risk management and disaster preparation plans in order to respond to extreme events; (5) reducing the impact of other stressors on ecosystems and build resilience in iconic tourism features such as coral reefs and mangroves, and (6) educating tourists to improve understanding the impacts of climate change over those stemming from local stresses [*Scott et al.*, 2012a; *Scott et al.*, 2012b].

30.6.2.3. Shipping

International shipping accounts for > 80% of world trade by volume [*UNCTAD*, 2009a; b] and ~3% of global CO_2 emissions from fuel combustion (IMO, 2009), although emissions are expected to increase 2-3 fold by 2050 [*UNCTAD*, 2009b]. However, increased shipping, and the concurrent increase economic activity, will increase the emission of black carbon. The black carbon will in turn increase warming and ice-melt that further increases economic activity and shipping [*Lack and Corbett*, 2012]. Changing shipping routes [*Borgerson*, 2008], shifts in grain production and global markets, as well as new fuel and weather-monitoring technology, may alter these emission patterns. Higher temperatures and extreme weather events, intensified by climate change, may interrupt ports and transport routes more frequently, damage infrastructure, and introduce additional dangers to ship, crew and the environment [*UNCTAD*, 2009a; b].

Climate change may benefit maritime transport by reducing Arctic sea ice, shortening sailing distances between key ports [*Borgerson*, 2008] and thus decreasing total GHG emissions from ships. Currently, reliability of this route limits its use [*Schøyen and Bråthen*, 2011], and the potential full operation of the Northwest Passage and Northern Sea Route would require a transit management regime, regulation (e.g. navigation, environmental, safety and security) and a clear legal framework to address potential territorial claims that may arise, with a number of countries having direct interests in the Arctic.

30.6.2.4. Offshore Energy and Mineral Resource Extraction and Supply

The marine oil and gas industry is a key driver of energy and climate scenarios due to its role in supplying the liquid fossil fuels that are key contributors to greenhouse gas emissions. The industry also faces potential impacts from climate change on its ocean-based activities. Over 100 oil and gas platforms were destroyed in the Gulf of Mexico by the unusually strong hurricanes, Katrina and Rita. Other impacts to oil pipelines and production facilities ultimately reduced US refining capacity by 20% (AR5 SREX). The increasing demand for oil and gas has pushed operations to waters 2,000 m deep or more, far beyond continental shelves. The very large-scale moored developments involved are exposed to greater hazards and higher risks, most of which are not well understood by existing climate/weather projections. Although there is a strong trend towards seafloor well completions with a complex of wells, manifolds and pipes that are not exposed to surface forcing, these systems face different hazards from instability and bottom scouring from deep sea currents of the unconsolidated sediments [*Randolph et al.*, 2010]. Impacts from warming oceans on sea floor stability are widely debated due largely to uncertainties about the effects of methane and methane hydrates [*Archer et al.*, 2009; *Geresi et al.*, 2009; *Sultan et al.*, 2004]. The principle threat to oil and gas extraction in maritime settings is the impact of extreme weather on oil and gas extracting infrastructure [*Kessler et al.*, 2011], and this threat is likely to increase given that future storm systems are expected to have greater energy [*Emanuel*, 2005; *Knutson et al.*, 2010; *Trenberth and Shea*, 2006]. Events such as Hurricane Katrina in 2005 have illustrated challenges likely to arise for this industry with projected increases in storm intensity [*Cashell et al.*, 2005; *Cruz and Krausmann*, 2008]. In this regard, early warning systems and preparation planning offer some potential to reduce the impact of extreme events [*IPCC*, 2012].

30.6.3. Health and Social Vulnerability

30.6.3.1. Disease

Changing patterns of disease, water and food security, human settlements, extreme climatic events, and population growth and migration are the major threats to public health related to climate change [*Costello et al.*, 2009]. Evidence of linkages between climate change, the Ocean and disease are *limited*, although there is *medium agreement* that climate change has and will influence the frequency and incidence of disease in corals, molluscs and a range of other invertebrates [*Bruno et al.*, 2007; *Harvell et al.*, 2002a]. The predominately negative impacts are likely to be more serious in low-income countries such as southeast Asia, southern and east Africa, and various sub-regions of South America [*Patz et al.*, 2005], countries which also have under-resourced health systems [*Costello et al.*, 2009]. Many of the influences are directly or indirectly related with basin-scale changes in the Ocean (e.g.

temperature, rainfall, plankton populations, ocean circulation; 11.2.5.1)[*McMichael et al.*, 2006], which include the spread of pathological diseases, seafood diseases, biological invasion and ballast-water discharge. Climate change impacts on the Ocean may influence the distribution of vector-borne diseases like Cholera, malaria and salmonella. The frequency of cholera outbreaks induced by *Vibrio cholerae* and other enteric pathogens show correlated multi-decadal fluctuations of ENSO and plankton blooms which may provide insight into how these disease may change with projected rates of ocean warming (11.2.5.1, [*Colwell*, 1996; *Myers and Patz*, 2009; *Pascual et al.*, 2000; *Patz et al.*, 2005; *Rodo et al.*, 2002]. The incidence of diseases such as ciguatera also shows a link to ENSO, with ciguatera becoming more prominent after periods of elevated sea temperature (e.g. ENSO). This indicates that ciguatera may become more frequent in a warmer climate [*Llewellyn*, 2010].

30.6.3.2. Security of Social Benefits and Fisheries

Climate change impacts on open-ocean fish populations are expected to affect the economics of fishing and the livelihood security of fishing nations because of changes in the price and value of catches, fishing costs, income to fishers and fishing companies, national labour markets, and industry re-organisation [*Sumaila et al.*, 2011]. A study of the potential vulnerabilities of national economies to the effects of climate change on fisheries concluded that Malawi, Guinea, Senegal, Peru, Columbia, Bangladesh, Cambodia, Pakistan, and Yemen are most vulnerable [*Allison et al.*, 2009]. In contrast, countries at high latitudes are likely to experience increases in their potential fisheries catch [*Cheung et al.*, 2010] although there are many uncertainties (*medium confidence*; 30.5.1). Fisheries provides 50 to 90% of dietary animal protein in rural areas of many Pacific countries, providing up to 20% of the GDP of some countries, with licence fees from foreign fishing fleets providing up to 40% of government revenue [*Bell et al.*, 2013a]. Tuna are very responsive to changing sea temperatures. In the western equatorial Pacific, nations with the greatest dependence on tuna fisheries (e.g. Kiribati, Nauru, Tuvalu, Tokelau) are likely to benefit as tuna distributions shift eastward as global and ocean temperature change [30.5.1]. Climate change on the other hand will decrease food security through impacts on fisheries associated with coral reefs and mangroves (estimated loss of 20% by 2050)[*Bell et al.*, 2013a].

30.6.4. Ocean-Based Mitigation

30.6.4.1. Deep Sea Carbon Sequestration

The economic impact of deliberate CO_2 sequestration beneath the sea floor has earlier been reviewed [*Metz et al.*, 2005]. Active CO_2 sequestration from co-produced CO_2 into sub-sea geologic formations is proceeding in the North Sea, and in the Santos Basin offshore Brazil. It is likely that these activities will increase as off shore oil and gas production increasingly produces fields with high CO_2 in the source gas and oil. Significant risks from the injection of high levels of CO_2 into deep ocean waters have been identified for deep sea organisms and ecosystems. These risks are similar to those discussed previously with respect to ocean acidification and are also likely to exacerbate declining oxygen levels and trophic networks in deep water areas [*Seibel and Walsh*, 2001].

There are significant issues within the decision frameworks regulating these activities. Dumping of any waste or other matter in the sea including the seabed and its subsoil is strictly prohibited under the 1996 London Protocol (LP) except for those few materials listed in Annex I. The direct injection of CO_2 into sub-surface geological formations is generally considered to fall under the exception to the definition of “dumping” under the LP as “placement for a purpose other than the mere disposal thereof.” The LP was amended in 2006 to permit storage of CO_2 under the seabed. Specific Guidelines for Assessment of Carbon Dioxide Streams for Disposal into Sub-Seabed Geological Formations were adopted by the parties to the LP in 2007. The Guidelines take a precautionary approach to the process requiring Contracting Parties under whose jurisdiction or control such activities are conducted to issue a permit for the disposal subject to stringent conditions being fulfilled [*Rayfuse and Warner*, 2012].

30.6.4.2. Blue Carbon: Sequestering and Maintaining Carbon in Marine Ecosystems

Marine and coastal ecosystems such as mangroves and salt marsh store significant amounts of organic carbon, which has been referred to as 'Blue Carbon' by analogy to the ocean equivalent of sequestered carbon within forests and other terrestrial ecosystems (‘green carbon’). The measurements and recognition of the carbon sequestration value of marine ecosystems is in its infancy but may assume importance given that significant amounts of organic carbon are stored within ocean ecosystems such as sea grass beds and mangroves (e.g. sequestered carbon per square metre of mangrove is many times that of terrestrial forests). Assuming that the global trade in carbon matures, the strategy to protect and expand the sequestration of carbon within marine ecosystems may play an essential role in reducing the current higher flux of greenhouse gases such as carbon dioxide and methane to the atmosphere [*Mcleod et al.*, 2011].

30.6.5. Maritime Security and Related Operations

Climate change and its influence on the Ocean has become an area of increasing concern in terms of the maintenance of national security and the protection of countries’ citizens. These concerns have arisen as Nation States increasingly engage in operations ranging from humanitarian assistance in climate change related disasters to territorial issues exacerbated by changing coastlines, human communities, resource access and new seaways [*Kaye*, 2012; *Rahman*, 2012]. In this regard, increasing sea levels along gently sloping coastlines can have the seemingly perverse outcome that the territorial limits to the maritime jurisdiction of the State might be open to question as the distance from national baselines to the outer limits of the exclusive economic zone increases beyond 200 nm over time [*Schofield and Arsana*, 2012].

Changes in coastal resources may also be coupled with decreasing food security to compound coastal poverty and lead, in some cases, to increased criminal activities such as piracy, illegal fishing, and people smuggling and arms and drug trafficking [*Kaye*, 2012]. While the linkages have not been clearly defined in all cases, it is very likely that changes in the Ocean as result of climate change are likely to increase pressure on resources aimed at maintaining maritime security and countering criminal activity, disaster relief operations, and freedom of navigation. The size and shape of maritime security infrastructure may also require rethinking as new challenges present themselves as a result of climate change [*Rahman*, 2012]. Opportunities may also arise from changes to international geography such as formation of new ice free seaways through the Arctic, which may benefit some countries in terms of maintaining maritime security and access. On the other hand, new features such as these within the Ocean may also lead to increasing international tensions as States perceive new vulnerabilities from these changes to geography.

Like commercial shipping (30.6.2.3), Naval operations in many countries emit significant greenhouse emissions (e.g. US Navy emits around 2% of the national greenhouse gas emissions), [*Mabus*, 2010]. As a result, there are a number of substantial programs within navies around the world to reduce their greenhouse footprint through improved engine efficiency, reducing fouling of vessels, increasing the use of biofuels and nuclear technology for power generation, and other strategies. The push to reduce emissions by using renewable fuel sources has the very substantial and synergistic benefit of increasing independence from foreign sources of energy [*Rahman*, 2012].

30.6.6. Multi-Sector Synthesis, and Key Risks and Vulnerabilities

The Ocean interacts with almost all aspects of life on Earth. As a result, it is not instructive to assess the impacts of climate change on the Ocean as a series of isolated influences and impacts on sub-regions and sectors. Many aspects of the Ocean’s chemical and physical characteristics are changing rapidly, triggering high levels of change within the Ocean’s ecosystems. Given the direct dependence of hundreds of millions of people on ocean ecosystem services, many of the aspects of the changes discussed as part of this chapter are *very likely* to increase the risk of poverty, decrease food security, and increase social and economic dysfunction along coastlines throughout the world. At the same time, industries such as fishing and shipping will face increasing uncertainty concerning conditions within the Ocean, which may offer opportunities (e.g. increased access to Arctic resources and sea lanes) as well as significant challenges (e.g. rapidly moving and changing fisheries resources). Impacts from climate change are also *very likely* to interact with stressors not related to anthropogenic climate change. These changes may be antagonistic (i.e. dampening the influence of each change) or synergistic, amplifying the influence that each change would have had on its own. Our understanding of these interactions and how they will play out under rapid climate change is incomplete and uncertain. A better understanding of these interactions between climate change and other human related stressors is, consequentially, of central importance to the understanding of how we might adapt to the changes that are occurring and will occur within the Ocean.

Key risks and vulnerabilities due to climate change across ocean sectors are synthesised in Table 30-6 and range from changing ocean productivity, ecosystem regime shifts, migration of organisms and ecosystems, reorganisation of fisheries composition, increases in disease and invading organisms, and the impacts of sea level rise and changing weather patterns on coastal processes, industries, and people. In addition to these risks and vulnerabilities, are the important implications of sea level rise and the loss of summer sea ice for the definition of maritime zones and aspects of national security. Issues have been discussed in previous chapters and section of the present chapter. The ramifications of these changes are also outlined in Table 30-6 including impacts on human communities and industries associated with coastal and oceanic sectors from fishing and tourism to maritime security.

30.6.7. Global Frameworks for Decisionmaking

As outlined here, there is little credible doubt that the Ocean is changing fundamentally as a result of the activities of humans at local and global scales (*very high confidence*). We are only just beginning to understand both the scale and complexity of these changes, highlighting the critical importance of rapidly reducing the emissions of greenhouse gases while at the same time seeking strategies to reduce the impact of changing physical and chemical circumstances and ecosystems across the planet. In the latter case, strong frameworks for global decision-making are critical for devising and implementing adaptation and mitigation strategies for reducing the impacts of climate change (Table 30-6, column 6). These frameworks if they continue to be successful, represent opportunities for global cooperation and the development of international, regional and national policy responses to the challenges posed by the changing ocean [*Kenchington and Warner*, 2012; *Tsamenyi and Hanich*, 2012; *Warner and Schofield*, 2012].

[INSERT TABLE 30-6 HERE
Table 30-6: Key risks and vulnerabilities, as well as ramifications, adaptation options and frameworks for decision-making within a number of areas discussed in chapter 30. Symbols are as follows: T = sea temperature; UW = upwelling; OA = ocean acidification; NU = nutrient concentration; IC = ice cover; SS = storm strength, SLR = sea level rise (↑ = Increased; ↓ = decreased; italics = uncertain). Acronyms are: CBD (Convention on Biological Diversity), CTI (Coral Triangle Initiative), GEF (Global Environment Facility), IHO (International Hydrographic Organization), ILO (International Labour Organisation), IOM (International Organisation of Migration), ISPS (International Ship and Port Facility Security), LOSC (1982 Law of the Sea Convention), MARPOL (International Convention for the Prevention of Pollution From Ships), PACC (Pacific Adaptation to Climate Change Project), PEMSEA (Partnerships in Environmental Management for the Seas of East Asia), RFMO (Regional Fisheries Management Organisations), SPREP (Secretariat of the Pacific Regional Environment Programme), UNCLOS (United Nations Convention on the Law of the Sea), UNHCR (United Nations High Commissioner for Refugees), and WHO (World Health Organisation).]

The United Nations Convention on the Law of the Sea (LOSC) was a major outcome of the third UN Conference on the Law of the Sea (UNCLOS III). The European Union and 164 countries have joined in the Convention although it is uncertain as to the extent to which the Convention codifies international maritime law. LOSC replaced earlier frameworks that were built around the ‘freedom of the seas’ concept and which limited territorial rights to 3 nm off a coastline. It provides a comprehensive framework for the legitimate use of the ocean and its resources, including maritime zones, navigational rights, protection and preservation of the marine environment, fishing activities, marine scientific research, and mineral resource extraction from the deep seabed beyond national jurisdiction. The relationship between climate change and LOSC is not clear and depends on interpretation of the key elements within the UNFCCC and Kyoto Protocol [*Boyle*, 2012]. However, the LOSC provides mechanisms to help structure adaptation in response to challenges posed by climate change. In a similar way, there is a wide range of other policy and legal frameworks that structure and enable responses to the outcomes of rapid anthropogenic climate change in the oceans.

Global frameworks for decision-making are increasingly significant in the case of ocean areas, most of which fall outside national boundaries [*Elferink*, 2012; *Warner*, 2012]. While around 50% of the Earth's surface is occupied by ocean resources that are outside the exclusive economic zones and continental shelves of the world's nations (high seas and deep seabed beyond national jurisdiction), there are increasing calls for more effective decision frameworks aimed at regulating fishing and other activities (e.g. bioprospecting) within these ocean 'commons'. These international frameworks will become increasingly valuable as nations respond to changing fisheries resources and the state of ocean ecosystems that stretch across national boundaries. One such example is the multilateral cooperation that was stimulated by President Yudhoyono of Indonesia in August 2007 that led to the Coral Triangle Initiative on Coral Reefs, Fisheries, and Food Security (CTI) which involves region-wide (involving 6.8 million km^2 including 132,000 km of coastline) cooperation between the governments of Indonesia, Philippines, Malaysia, Papua New Guinea, Solomon Islands and Timor Leste on reversing the decline in coastal ecosystems such as coral reefs [*Clifton*, 2009; *Hoegh-Guldberg et al*., 2009; *Veron et al*., 2009]. Given that coral reefs, mangroves and key resources such as tuna stocks stretch across national boundaries, partnerships such as that begun in Southeast Asia have the potential to provide key frameworks to address issues such as interaction between the over-exploitation of coastal fishing resources and the recovery of reefs from mass coral bleaching and mortality, and the implications of the movement of valuable fishery stocks beyond waters under national jurisdiction. The recently announced World Bank Global Partnership for Oceans announced (March 28, 2012) aims to create a global framework in which to engage governments, international organisations, civil and public sector interests in both understanding and finding solutions to key issues such as overfishing, pollution, and habitat destruction [*GPO*, 2012]. Similarly, the Areas Beyond National Jurisdiction (ABNJ, Global Environment Facility) Initiative has been established to promote the efficient, collaborative and sustainable management of fisheries resources and biodiversity conservation across the open ocean.

Global partnerships are also essential for providing support to many nations that often do not have the scientific or financial resources to solve the challenges that lie ahead [*Busby*, 2009; *Mertz et al*., 2009]. In this regard, international networks and partnerships are particularly significant in terms of assisting nations in developing local adaptation solutions to their ocean resources. By sharing common experiences and strategies through global networks, nations have the chance to tap into a vast array of options with respect to responding to the impacts of climate change on global resources.

30.7. Concluding Remarks: Emerging Issues, Data Gaps, and Research Needs

Our understanding of the changes that are occurring within the Ocean as a result of climate change is still forming, as is our ability to predict how future changes will unfold. We have *very high confidence* that many aspects of the Ocean have and will change over the coming decades in response to increasing levels of greenhouse gases in the atmosphere. The high rates of change in key variables such as temperature, pH, carbonate chemistry and oxygen levels (30.3) are *virtually certain* to drive fundamental changes in ocean ecosystem structure and function.

30.7.1. Major Conclusions

There is *robust evidence, high agreement and high confidence* that the physical, chemical and biological characteristics of the Earth Ocean are changing rapidly as a result of human activities that have increased the atmospheric concentrations of greenhouse gases such as carbon dioxide (30.3-30.5). Many of these changes are large-scale, interconnected and have no analogue in thousands if not millions of years (*very high confidence*), and involve changes to the physiology and ecology of the ocean, as well as ecosystem processes such as primary productivity, marine calcification and gas exchange (*high confidence*). A comprehensive analysis of recent literature, for example, reveals that 84% of recent changes reported in the peer-reviewed scientific literature are consistent with changes expected under climate change (*high confidence*). Organisms are rapidly moving to higher latitudes with 'mobile' organisms (phytoplankton, zooplankton and fish) moving at the most rapid rates (Figure 30-

11B). At the same time, seasonal changes that drive key events in organism life cycles are advancing by 2-5 days.decade^{-1}. These changes approach and exceed in many cases those seen for terrestrial organisms and ecosystems. These fundamental changes suggest increasing asynchrony between organisms and their competitors and food, as well as the increasing likelihood of ecosystem assemblages that have no recent analogue.

Many ocean sub-regions (e.g. SES, EBUE, EUS, and STG) are experiencing changes in the extent to which upper ocean waters mix with deeper layers (*high confidence*, Box 30-1). These changes affect the supply of nutrients to the surface waters in the ocean, and have serious ramifications for the primary production of ocean ecosystems as well oxygen concentrations in many parts of the ocean (*high confidence*). In several of the world's semi-enclosed oceans (Baltic, Black, and Mediterranean Seas), ocean warming is leading to greater water column stability, which in turn has reduced mixing and primary productivity, leading to increased hypoxia at depth. In the EBUE sub-regions, however, increasing wind strength may be driving increased upwelling and consequently greater levels of primary productivity. In the latter case, however, higher levels of primary productivity and a subsequently higher flux of organic carbon into the deep ocean is resulting in reduced oxygen levels at depth. While we do not have a complete understanding of the changes to the oxygen content of the Ocean, changes in such a fundamental variable should be of great concern.

Our understanding of the influence of climate change on ocean systems has been challenged by variability which operates on a variety of spatial and temporal scales, and which can amplify the impacts of ocean warming and acidification. While most ocean regions have experienced significant changes a few regions have not. Short to long-term patterns of variability such as ENSO, PDO, AMO and NAO have complicated the interpretation of recent changes within the ocean. Despite this variability, there is an undeniable trend in ocean temperature and the response of key marine organisms and ecosystems.

The impacts and implications of the current changes in the ocean differ from sector to sector. In many parts of the world, fisheries such as those associated with tropical coastlines are expected to continue to decline. In other regions, the distribution and abundance of key fish stocks such as tuna will change over time impacting fishing industries in regions such as the Pacific and Indian oceans. Some regions may benefit while others may find it increasingly hard to obtain fish stocks as they move to new parts of the Ocean in response to changing sea temperatures. HLSBS are critically important to 36% of the world's fisheries. Fundamental changes as a result of ocean warming and acidification are occurring in the composition of plankton communities which are driving changes to the species composition and abundance of key fisheries (30.14 B). Ecological regime shifts have occurred with substantial impacts on key fisheries and dependent industries (Figure 20.15B), and are *very likely* to continue as warming continues. Climate change may lead to greater productivity in some fisheries through warmer temperatures, increased upwelling and reduced sea ice.

The economic well-being of sectors such as tourism is *very likely* to be strongly influenced by changes in regional weather patterns, rising sea levels, extreme events and the perception of risk. In addition to changing weather patterns, heat stress events such as mass coral bleaching and mortality are likely to increase as temperatures increase, bringing the future of the highly productive coastal ecosystems such as coral dominated coral reefs into question (Figure 30-12; Box CC-CR). The impacts of losing these highly productive and biologically diverse ecosystems is *likely* to change the tourist attractiveness of some regions as well is the livelihoods of millions of people that live in close association with the world's coastal areas.

There are numerous other consequences of climate change on the Ocean. In some cases, there may be advantages for international shipping from warmer and less ice-prone waters. On the other hand, sectors such as fishing and tourism will have to deal with a greater level of uncertainty and change, which has ramifications for human health and security, as well as current and future tourist opportunities. The changing conditions within the world oceans also represent challenges for industries intent on exploiting offshore energy and mineral resources. Increasing storm strength along with larger wave heights and wind velocities present increasing risks to these industry sectors. These changes in turn impact maritime security operation as well as the capacity of these elements to respond to environmental impacts associated with anthropogenic climate change.

30.7.2. Emerging Themes

The rapid changes that have been observed within the world oceans are an emerging theme within our understanding of climate change. Until recently, the impacts of climate change on ocean systems gained much less attention than those being observed within terrestrial areas of the planet. From the detection and attribution analysis undertaken here, however, it should be clear that fundamental changes in the physical, chemical and biological characteristics of the ocean are occurring rapidly and have implications for people everywhere.

The decrease in the concentration of oxygen within the ocean core and across many parts of the ocean is an emerging theme. The decrease in oxygen levels is a consequence of warming and stratification of the water column in some areas, changes in local weather patterns in others, and temperature influences on the ratio of rate of metabolism. The decline in oxygen concentrations in large parts of the ocean is of great concern given the potential impacts that spreading hypoxia could have for marine species and ecosystems. In this respect, projected increases in sea temperature under the current Business-As-Usual scenarios are likely to rapidly enhance water column stratification, increase bacterial metabolism and consequently drive major expansion in deep-ocean areas that are currently low in oxygen. Based on the impacts experienced so far from the 0.8°C increase in average global temperature, future changes are *very likely* to threaten many significant ocean ecosystems and fisheries. There are also fundamental implications for the ability of the ocean to provide planetary services such as maintaining the oxygen content of the atmosphere.

The changes in wind stress and ocean-atmosphere exchange is another emerging theme. Changes to water column mixing and ventilation have driven changes to productivity and other aspects such as oxygen concentration in a number of key areas of the world's oceans. While there is considerable discussion about how climate change will affect upwelling systems, there is concern that changes to the increase in land-ocean thermal gradient could result in stronger upwelling in some areas while others decrease (Figure 30-15). At present, there is little information and understanding about the response of these important areas of fisheries production in the rapidly warming world.

The impacts of ocean acidification on marine organisms and ecosystems (Box CC-OA) has emerged as a major concern especially given the robust evidence that the current chemistry of the ocean is outside where it has been for at least 1 million years. At current rates of increase atmospheric CO_2, the acidity of the ocean will surpass any seen over the last 40 million years [*Hoegh-Guldberg et al.*, 2007; *Raven et al.*, 2005]. The growing literature from the past five years has increasingly documented a major array of changes from the reduced calcification of coral reefs and pteropods, to impacts on animal reproduction, navigation, and olfaction. Ocean acidification is rapidly emerging as a very serious yet uncharted risk for all ocean sub-regions, although the earliest demonstrated impacts of changing pH and carbonate ion concentrations are being felt at higher latitudes due to the colder temperatures and hence greater flux of CO_2 entering these waters.

Understanding how the productivity of the Ocean is likely to change in a warmer and more acidic ocean is a significant emerging theme. Changes to the physical and chemical nature of ocean waters are also driving changes in the distribution and abundance of primary production (Figures 30.15, 30.15). These changes are beginning to have fundamental and large-scale influences on the distribution and abundance of primary productivity, which has implications for both fisheries as well as the flux of organic carbon into the deep ocean. While the current decreases in productivity that have been reported in the major ocean basins need to be considered in the light of natural climate variability such as ENSO and PDO, it is necessary that we develop a greater understanding of the potential implications of these rapid changes in ocean productivity. In this respect, a serious decrease in ocean services may be underway if ocean productivity continues to decrease over and above the background variability within the ocean climate systems. Extending these changes over the coming decades and century would be the basis for serious global concern. In combination with changes to sea temperature, changes to the distribution of ocean productivity has serious implications for the productive pelagic top predator fisheries that many countries depend on (30.5.2, 30.5.6; Figure 30-15). Understanding these current changes should be an urgent priority of the international community.

30.7.3. Research and Data Gaps

Despite the fact that Earth is dominated by the Ocean, we are only beginning to understand the physical, chemical and biological processes that underpin its ability to provide a range of ecosystem and planetary services. This situation has arisen because of the relative difficulty of accessing ocean environments, which has meant that comprehensive measurements of many parameters and ocean regions have only been available for the past 50 years or less. Given the importance of the world's oceans, it is an imperative that we increase our understanding of how climate change (including ocean acidification) are likely to influence the structure and function of ocean systems.

Understanding how wind stress will change in a warmer world is particularly important given the role of wind in water column mixing and nutrient availability, and hence primary and fisheries production. This gap in our understanding is crucial given the reliance of humans on the fisheries associated with upwelling regions throughout the world. Similarly, improving our understanding of the changes that are occurring within the STGs of the major ocean basins is especially significant given the strong background influence of short to long-term natural climate variability such as ENSO, PDO, and AMO. Understanding how the variability that key fisheries currently face interacts with ocean warming and acidification represents a significant knowledge and research gap.

The deep ocean below 1000 m is the most abundant habitat on the planet yet it is the region about which we know the least. In this respect, increasing our understanding of deep-ocean habitats and how these may be changing under the influence of both climate change and non-climate change factors is of great importance. Linkages between changes occurring in the surface layers of the ocean and those associated with deep regions of the world's oceans are particularly important in the light of understanding how rapidly changes are occurring as well as implications for the metabolic activity and oxygen content of deep water habitats.

While research focused on the responses of marine ecosystems to climate change has increased substantially over the past decade, much of this effort is clustered in particular sub-regions (North Pacific and North Atlantic Oceans). It will be essential to expand the number and geographical spread of studies focused on how the Ocean and its ecosystems are changing with respect to global warming and acidification. Equally, many organisms are underrepresented in the studies. Bony fish, copepods and sea birds have received a lot of attention in the scientific literature (albeit located in heavily studied sub-regions), while macroalgae (particularly brown algae), benthic invertebrates (e.g. molluscs, barnacles, cnidarians), and dinoflagellates have been the focus of a moderate number of studies. Many other organisms have not received much attention, illustrating the need for an expansion of the focus of future studies to include these organisms, which are often crucial within ocean ecosystems and processes.

We are also in an early stage of understanding of how sectors such as fishing are likely to be affected by the current fundamental changes to the Ocean. In this respect, it is highly likely that the current structure, distribution, and abundance of fishery stocks and industries are going to be transformed as we head towards a much warmer world. Developing a better understanding of how to adapt fisheries infrastructure and strategy to these changing conditions is of enormous importance. In the broadest setting, it is an imperative that we also develop a greater understanding of how changes to storm strength, sea level and a range of other factors are going to influence other activities such as shipping, energy and mineral extraction, and other human activities, especially those located in the populous coastal sub-regions of the world.

Lastly, the current expansion of technologies that can allow the automated exploration of the ocean represents a very significant opportunity to rapidly improve our understanding of one of the most fundamentally important features of our planet. Given that our understanding of how ocean systems will respond to increased greenhouse gas concentrations has lagged behind our understanding of terrestrial and atmospheric change, it is vital that these new technologies be applied at a scale which can begin to understand and project how ocean systems are likely to change over the coming decades and century. When combined with the increasing opportunities offered by satellite-based remote sensing as well is an increasing set of research activities at all depths within the ocean, these technologies represent a significant opportunity to understand both our planet and the changes on it due to human activities. Hopefully these new insights and understanding will assist humanity to not only understand but ultimately solve the massive challenges presented by anthropogenic climate change (including ocean acidification) for the world’s Ocean.

Frequently Asked Questions

FAQ 30.1: Can we reverse the climate change impacts on the ocean?

Greenhouse gas emissions have resulted in major physical and chemical changes in our oceans. In less than 150 years, we have caused changes in the oceans not seen for millions of years. These changes can be reversed if emissions are stopped, but not in our lifetime. Oceans are warming slower than land because of their higher heat capacity and the slow mixing of warmer surface waters into the deep ocean (~2,000 yr). These different characteristics of the ocean mean that it will take centuries for ocean warming to reverse once greenhouse gas emissions are reduced. As CO_2 enters the oceans it also alters ocean chemistry (reducing pH). Chemical changes to the ocean will take thousands of years to reverse.

FAQ 30.2: How can we use non-climate factors to manage climate change?

Natural systems are exposed to a range of climate change and non-climate factors. We need to manage the combined impacts of climate and other human activities such as pollution, eutrophication, habitat destruction, invasive species and fishing. These activities combine in different ways with climate change, with some acting in opposition (antagonistic) while others act together to produce an enhanced effect (synergistic). Where we find synergistic interactions, we can devote our management efforts to reducing the non-climate activities thus minimizing degradation of natural systems. For example, maintaining coastal water quality will partially alleviate the impact of thermal stress and aid recovery of seagrass beds. Identifying the type of interactions between climate and human activities will be crucial for managing climate change impacts on natural systems. Developing ecosystem-based management of fishery resources where climate-induced changes in the productivity are implemented will help maintaining sustainable fishery under climate change.

FAQ 30.3: Does slower warming mean less impact on plants and animals?

The opportunities for adapting and accommodating climate change are generally higher at slower rates of environmental change. However, there are now many observations which suggest that even small amounts of warming will lead to significant changes in the structure and function of marine ecosystems. Despite less warming in equatorial sub-regions than elsewhere, many tropical species are under threat from future warming as they are already near their upper thermal tolerance limits. Similarly, despite slower warming over ocean than land, bands of equal temperature (isotherms) are migrating polewards at similar or faster rates in the ocean implying that marine species will have to move at rates comparable to, or faster than, land species to track thermal environments. Rates of change in seasonal temperature peaks are also similar over ocean and land, implying comparable shifts in timing of life history events such as earlier reproduction in spring. Therefore, even the slower warming in the tropics and in the oceans will pose challenges to species and reorganize natural systems.

FAQ 30.4: How will marine primary productivity change?

Changes in marine primary productivity in response to climate change remain the single biggest uncertainty in predicting the magnitude and direction of future changes in fisheries and marine ecosystems. Drifting microscopic (1-100 μm) plants known as phytoplankton are the dominant marine primary producers. Their photosynthetic activities provide approximately half the oxygen we breathe, supports most marine food webs, and influences global biogeochemical cycles. There is considerable uncertainty in observed changes in primary production globally, with some studies showing declines and others increases. Regionally, there is mounting evidence of productivity increases in the world's most productive (upwelling) systems, some evidence that productivity in the highest latitudes of the spring-bloom ecosystems and polar areas is increasing. Longer satellite time series, maintenance of in-water time series, and more emphasis on modeling future primary productivity are needed.

FAQ 30.5: Can we expect actual loss of marine life and/or the creation of true ocean dead zones under climate change?

Warming of the ocean by 2 degrees will reduce oxygen solubility by about 14 micromoles per kg at typical mid-water temperatures (5º - 7ºC). In some areas of the ocean such as those at a few hundred meters depth off the west coast of the Americas, and in the northern Arabian Sea, where oxygen levels are already low, we may expect conditions in which oxygen is virtually zero, with resulting loss of life. A smaller additional ocean oxidation capacity is represented by the presence of dissolved nitrate which can be used by bacteria as a chemical resource thus delaying the absolute loss of oxygen. This process is occurring regionally today, and oceanic nitrate losses occurred in the pre-industrial ocean. But the combined oxidation capacity of oxygen and nitrate will be exceeded, and once this occurs, toxic hydrogen sulfide can appear in the ocean water column. This has not been seen in recorded history although short term sporadic eruptions of sulfide from the sea floor have been observed. There is evidence for the presence of sulfide oxidizing bacteria in the sub-oxic ocean today. The reduction of dissolved oxygen from solubility effects alone greatly underestimates the case. Ocean data shows that only ~15% of the observed changes can be attributed to solubility reduction from warming; ~85% is attributable to the effects of increased bacterial activity and reduced ventilation by the atmosphere in the more stratified upper ocean. If these trends hold then ~5x greater oxygen losses could occur at depth with more widespread true dead zones at depth and loss of marine life in affected ocean regions.

Cross-Chapter Boxes

Box CC-CR. Coral Reefs

[Jean-Pierre Gattuso (France), Ove Hoegh-Guldberg (Australia), Hans-Otto Pörtner (Germany)]

Coral reefs are shallow-water structures made of calcium carbonate mostly secreted by reef-building (scleractinian) corals and encrusting macroalgae. They occupy less than 0.1% of the ocean floor yet play multiple important roles throughout the tropics. About 275 million people live within 30 km of a coral reef (Burke et al., 2011) and are likely to derive some benefits from the ecosystem services that coral reefs provide (Hoegh-Guldberg, 2011) including those from provisioning (food, construction material, medicine), regulating (shoreline protection, water quality), supporting services (oxygen supply) and cultural (religion, tourism). This is especially true in small islands (29.3.3.1).

Most human-induced disturbances to coral reefs were local (e.g., coastal development, pollution, nutrient enrichment and overfishing) until the early 1980s when global and climate-related disturbances (ocean warming and acidification) began to occur. Temperature and seawater acidity are two of the most important environmental variables determining the distribution of coral reefs (Kleypas et al., 2001). As corals are centrally important as ecosystem engineers (Wild et al., 2011), the impacts on corals have led to widespread degradation of coral reefs.

A wide range of climatic and non-climatic stressors affect corals and coral reefs and negative impacts are already observed (5.4.2.4, 30.5.3, 30.5.6). Bleaching involves the breakdown and loss of endosymbiotic algae (genus *Symbiodinium*), which live in the coral tissues and play a key role in supplying the coral host with energy and nutrients (Baker et al., 2008) (see 6.2.5 for physiological details and 30.5 for a regional analysis). Mass coral bleaching and mortality, triggered by positive temperature anomalies, is the most widespread and conspicuous impact (Fig. 5X; see Sections, 5.4.2.4, 6.2.5, 25.6.2, 30.5 and 30.8.2). For example, the level of thermal stress at most of the 47 reef sites where bleaching occurred during 1997-98 was unmatched in the period 1903 to 1999 (Lough, 2000). Elevated temperature along with ocean acidification reduces the calcification rate of corals (*high confidence*; 5.4.2.4), and may tip the calcium carbonate balance of reef frameworks towards dissolution (*medium evidence and agreement*; 5.4.2.4). These changes will erode fish habitats with cascading effects reaching fish community structure and associated fisheries (*robust evidence, high agreement*, 30.5).

Around 50% of all coral reefs have experienced medium-high to very high impact of human activities (30-50% to 50-70% degraded; Halpern et al., 2008), which has been a significant stressor for over 50 years in many cases. As a result, the abundance of reef building corals is in rapid decline (1 to 2% per year, 1997-2003) in many Pacific and SE Asian regions (Bruno and Selig, 2007). Similarly, the abundance of reef-building corals has decreased by over 80% on many Caribbean reefs (1977 to 2001; Gardner et al., 2003), with a dramatic phase shift from corals to seaweeds occurring on Jamaican reefs (Hughes, 1994). Tropical cyclones, coral predators and coral bleaching have led to a decline in coral cover on the Great Barrier Reef (about 51% between 1985 and 2012; De'ath et al., 2012).

One third of all coral species exhibit a high risk of extinction, based on recent patterns of decline and other factors such as reproductive strategy (Carpenter et al., 2008). Although less well documented, non-coral benthic invertebrates are also at risk (Przeslawski et al., 2008). Fish biodiversity is threatened by the permanent degradation coral reefs, including in a marine reserve (Jones et al., 2004). While many factors, such as overfishing and local pollution, are involved in the decline of coral reefs, climate change through its pervasive influence on sea temperature, ocean acidity, and storm strength plays a very significant role.

There is *robust evidence* and *high agreement* that coral reefs are one of the most vulnerable marine ecosystems (Chapters 5, 6, 25, and 30). Globally, more than half of the world's reefs are under medium or high risk of degradation (Burke et al., 2011) even in the absence of climatic factors. Future impacts of climate stressors (ocean warming, acidification and sea level rise) will exacerbate the impacts of non-climatic stressors (*high agreement*, *robust evidence*). Even under optimistic assumptions regarding corals being able to rapidly adapt to thermal stress, one-third (9–60%, 68% uncertainty range) of the world's coral reefs are projected to be subject to long-term degradation under the RCP3-PD scenario (Frieler et al., 2013). Under the RCP4.5 scenario, this fraction increases to two-thirds (30–88%, 68% uncertainty range). If present day corals have residual capacity to acclimatize and/or adapt, half of the coral reefs may avoid high frequency bleaching through 2100 (*limited evidence, limited agreement*; Logan et al., sbm). Evidence of corals adapting rapidly, however, to climate change is missing or equivocal (Hoegh-Guldberg, 2012).

Damage to coral reefs has implications for several key regional services:

- *Resources*: Coral reefs produce 10-12% of the fish caught in tropical countries, and 20-25% of the fish caught by developing nations (Garcia & Moreno, 2003). Over half (55%) of the 49 island countries considered by Newton et al. (2012) are already exploiting their coral reef fisheries in an unsustainable way (13.X.X).
- *Tourism*: More than 100 countries benefit from the recreational value provided by their coral reefs (Burke et al., 2011). For example, the Great Barrier Reef Marine Park attracts about 1.9 million visits each year and generates A$ 5.4 billion to the Australian economy and 54,000 jobs (90% in the tourism sector; Biggs, 2011).
- *Coastal* protection: Coral reefs contribute to protecting the shoreline from the destructive action of storm surges and cyclones (Sheppard et al., 2005), sheltering the only habitable land for several island nations, habitats suitable for the establishment and maintenance of mangroves and wetlands, as well as areas for recreational activities. This role is threatened by future sea level rise, the decrease in coral cover, reduced rates of calcification and higher rates of dissolution and bioerosion due to ocean warming and acidification (5.4.2.4, 6.4, 30.5).

Coral reefs make a modest contribution to the global domestic product but their economic importance can be high at the country and regional scales (Pratchett et al., 2008). For example, tourism and fisheries represent on average 5% of the GDP of South Pacific islands (Laurans et al., 2013). At the local scale, these two services provide at least 25% of the annual income of villages in Vanuatu and Fiji (Pascal, 2011; Laurans et al., 2013).

Marine protected areas (MPAs) and fisheries management have the potential to increase ecosystem resilience and increase the recovery of coral reefs after climate change impacts such as mass coral bleaching (McLeod et al., 2009). Although they are key conservation and management tools, they are less effective in reducing coral loss from thermal stress (Selig et al., 2012) suggesting that they need to be complemented with additional and alternative strategies (Rau et al., 2012). Controlling the input of nutrients and sediment from land is an important complementary management strategy because nutrient enrichment can increase the susceptibility of corals to bleaching (Wiedenmann et al., 2012). There is also high confidence that, in the long term, limiting the amount of warming and acidity is central to ensuring the viability of coral reef systems and dependent communities (5.X.X and 30.5).

[INSERT FIGURE CR-1 HERE
Figure CR-1: A and B: the same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Coral cover at the time of bleaching was 95% bleached almost all of it severely bleached, resulting in mortality of 20.9% (Elvidge et al., 2004). Mortality was comparatively low due in part because these communities were able shuffle symbiont types to more thermo-tolerant types (Berkelmans and van Oppen, 2006; Jones et al., 2008). C and D: three CO2 seeps in Milne Bay Province, Papua New Guinea show that

prolonged exposure to high CO2 is related to fundamental changes in coral reef structures (Fabricius et al., 2011). Coral communities at three high CO2 (Fig. XB; median pHT 7.7, 7.7 and 8.0), compared with three control sites (Fig. XA; median pHT 8.02), are characterized by significantly reduced coral diversity (-39%), severely reduced structural complexity (-67%), low densities of young corals (-66%) and few crustose coralline algae (-85%). Reef development ceases at pHT values below 7.7. Photo credit: R. Berkelmans (A and B) and K. Fabricius (C and D).]

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Box CC-OA. Ocean Acidification

[Jean-Pierre Gattuso (France), Peter Brewer (USA), Ove Hoegh-Guldberg (Australia), Joan A. Kleypas (USA), Hans-Otto Pörtner (Germany), Daniela Schmidt (UK)]

Introduction

Anthropogenic ocean acidification and climate change share the same primary cause at the global level, the increase of atmospheric carbon dioxide (WGI, 2.2.1). Eutrophication and upwelling contribute to local ocean acidification (5.3.3.6, 30.5.4). Past and futures changes in chemistry are well known in the surface open ocean (WGI, 3.8.2 and 6.4.4) but are more difficult to project in the more complex coastal systems (5.3.3.6 and 30.5.2).

Chemistry and Projections

The fundamental chemistry of ocean acidification has long been understood: the uptake of CO_2 into mildly alkaline ocean results in an increase in dissolved CO_2 and reductions in pH, dissolved carbonate ion, and the capacity of seawater to buffer changes in its chemistry (*very high confidence*). The changing chemistry of surface seawater can be projected at the global scale with high accuracy from projections of atmospheric CO_2 levels. Time series observations of changing upper ocean CO_2 chemistry support this linkage (WGI Table 3.2 and Figure 3.17; WGII Figure 30-5). Projections of regional changes, especially in coastal waters (5.3.3.6), and at depth are more difficult; observations and models show with high certainty that fossil fuel CO_2 has penetrated at depths of 1 km and more. Importantly, the natural buffering of increased CO_2 is less in deep than in surface water and thus a greater chemical impact is projected. Additional significant CO_2 increases and pH decreases at mid-depths are expected to result from increases in microbial respiration induced by warming. Projected changes in open ocean, surface water chemistry for year 2100 based on representative concentration pathways (WGII, Figure 6.28) compared to preindustrial values range from a pH change of -0.14 unit with RCP 2.6 (421 ppm CO_2, +1 ºC, 22% reduction of carbonate ion concentration) to a pH change of -0.43 unit with RCP 8.5 (936 ppm CO_2, +3.7 ºC, 56% reduction of carbonate ion concentration).

Biological, Ecological, and Biogeochemical Impacts

The effects of ocean acidification on marine organisms and ecosystems have only recently been investigated. A wide range of sensitivities to projected rates of ocean acidification exists within and across organism groups and phyla with a trend for higher sensitivity in early life stages (*high confidence*; Kroeker et al., in press; 6.2.3-5, 6.3.4). A pattern of impacts, some positive, others negative, emerges for some processes and organisms (*high confidence*; Fig. X.C) but key uncertainties remain from organismal to ecosystem levels (Chap. 5, 6, 30). Responses to ocean acidification are exacerbated at high temperature extremes (*medium confidence*) and can be influenced by other drivers, such as oxygen concentration, nutrients, and light availability (*medium confidence*).

Experimental evidence shows that lower pH decreases the rate of calcification of most, but not all, sea-floor calcifiers such as reef-building corals (Box CC-CR, coralline algae (Raven, in press), bivalves and snails (Gazeau et al., in press) reducing their competitiveness compared to, e.g. seaweeds (Chap. 5, 6, 30). A reduced performance of these ecosystem builders would affect the other components of the ecosystem dependent on the habitats they create.

Growth and primary production are stimulated in seagrass and some phytoplankton (*high confidence*) and harmful algal blooms could become more frequent (*limited evidence, medium agreement*). Ocean acidification may significantly stimulate nitrogen fixation in the oceans (*limited evidence, low agreement*; 6.2.3, 6.3.4). There are few known direct effects on early stages of fish and adult fish remain relatively undisturbed by elevated CO_2. Serious behavioral disturbances were reported, mostly on larval and juvenile coral reef fishes (6.2.4).

Projections of ocean acidification effects at the ecosystem level are limited by the diversity of species-level responses. Natural analogues at CO_2 vents indicate decreased species diversity, biomass and trophic complexity of communities living on the sea-floor. Shifts in community structure have been documented in rocky shore environments (e.g., Wootton et al., 2008), in relation with rapidly declining pH (Wootton and Pfister, 2012). Differential sensitivities and associated shifts in performance and distribution will change predator-prey relationships and competitive interactions (6.2-3), which could impact food webs and higher trophic levels (*limited evidence, high agreement*).

There is *limited evidence* and *medium agreement* that some phytoplankton and mollusks can adapt to ocean acidification, indicating that the long-term responses of these organisms to ocean acidification could be less than responses obtained in short-term experiments. However, mass extinctions during much slower rates of ocean acidification in Earth history (6.1.2) suggest that evolutionary rates are not fast enough for sensitive animals and plants to adapt to the projected rate of change (*high confidence*).

The effect of ocean acidification on global biogeochemical cycles is difficult to predict due to the species-specific responses to ocean acidification, lack of understanding of the effects on trophic interactions, and largely unexplored combined responses to ocean acidification and other climatic and non-climatic drivers, such as temperature, concentrations of oxygen and nutrients, and light availability.

Risks

Climate risk is defined as the probability that climate change will cause specific physical hazards and that those hazards will cause impacts (19.5.2). The risks of ocean acidification to marine organisms, ecosystems, and ultimately to human societies, includes both the probability that ocean acidification will affect key processes, and the magnitude of the resulting impacts. The changes in key processes mentioned above present significant ramifications on ecosystems and ecosystem services (Fig. 19.3). For example, ocean acidification will cause a decrease of calcification of corals, which will cause not only a reduction in the coral's ability to grow its skeleton, but also in its contribution to reef building (*high confidence*; 5.4.2.4). These changes will have consequences for the entire coral reef community and on the ecosystem services that coral reefs provide such as fisheries habitat (*medium confidence*; 19.5.2) and coastal protection (*medium confidence*; Box CC-CR). Ocean acidification poses many other potential risks, but these cannot yet be quantitatively assessed due to the small number of studies available, particularly on the magnitude of the ecological and socioeconomic impacts (19.5.2).

Socioeconomic Impacts and Costs

The biological, ecological and biogeochemical changes driven by ocean acidification will affect several key ecosystem services. The oceans will become less efficient at absorbing CO_2, hence less efficient at moderating climate change, as their CO_2 content will increase (*very high confidence*). The impacts of ocean acidification on coral reefs, together with those of bleaching and sea level rise, will in turn diminish their role of shoreline protection in atolls and small island nations as well as their direct and indirect benefits on the tourism industry (*limited evidence, high agreement*; Box CC-CR).

There is no global estimate of the observed or projected economic costs of ocean acidification. The production of commercially-exploited shelled mollusks may decrease (Barton et al., 2012) resulting in an up to 13% reduction of US production (limited evidence, low agreement; Cooley and Doney, 2009). The global cost of production loss of mollusks could be over 100 billion USD by 2100 (Narita et al., 2012). The largest uncertainty is how the impacts on prey will propagate through the marine food webs and to top predators. Models suggest that ocean acidification will generally reduce fish biomass and catch (*limited evidence, high agreement*) and that complex additive, antagonistic and/or synergistic interactions will occur with other environmental (warming) and human (fisheries management) factors (Branch et al., 2012; Griffith et al., 2012). The annual economic damage of ocean-acidification-induced coral reef loss by 2100 has been estimated, in 2009, to be 870 and 500 billion USD, respectively for A1 and B2 SRES emission scenarios (Brander et al. 2012). Although this number is small compared to global GDP, it represents a large proportion of the GDP of some regions or small island states which rely economically on coral reefs.

Adaptation and Mitigation

The management of ocean acidification comes down to mitigation of the source of the problem and adaptation to the consequences (Rau et al., 2012; Billé et al., sbm). Mitigation of ocean acidification through reduction of atmospheric CO_2 is the most effective and the least risky method to limit ocean acidification and its impacts. Climate geoengineering techniques based on solar radiation management would have no direct effect on ocean acidification because atmospheric CO_2 would continue to rise (6.4.2). Techniques based on carbon dioxide removal could directly address the problem but their effectiveness at the scale required to ameliorate ocean acidification has yet to be demonstrated. Additionally, some ocean-based approaches, such as iron fertilization, would only re-locate ocean acidification from the upper ocean to the ocean interior, with potential ramifications on deep water oxygen levels (Williamson and Turley, 2012; 6.4.2; 30.3.2.3 and 30.5.7). Mitigation of ocean acidification at the local level could involve the reduction of anthropogenic inputs of nutrients and organic matter in the coastal ocean (5.3.4.2). Specific activities, such as aquaculture, could adapt to ocean acidification within limits, for example by altering the production process, selecting less sensitive species or strains, or relocating elsewhere. A low-regret approach is to limit the number and the magnitude of drivers other than CO_2. There is evidence, for example, that reducing a locally determined driver (i.e. nutrient pollution) may substantially reduce its synergistic effects with a globally determined driver such as ocean acidification (Falkenberg et al., 2013).

[INSERT FIGURE OA-1 HERE
Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley & Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (IPCC AR5 WG1 report, Figure 6.28). C: Effect of near future acidification on major response variables estimated using weighted random effects meta-analyses, with the exception of survival which is not weighted (Kroeker et al., in press). The effect size indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a significant effect.]

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Table 30-1: Percent area of the ocean, primary productivity and fisheries catch (production) for major sub-regions of the ocean (for location of sub-regions, see Figure 30-1).

Ocean sub-region		**Area (%)**	**Primary Productivity (%)***	**Fishery Productivity or Long-term Fish Catches (%)****	**Relevant IPCC regions (Chapters)**
1. High-latitude Spring-bloom System (HLSBS)	Northern Hemisphere	10.60	22.74	29.20	*23-24, 26,28*
	Southern Hemisphere	14.40	20.55	6.82	*22, 25, 28*
2. Equatorial Upwelling Systems (EUS)		8.20	9.01	4.68	*22,27,29*
3. Semi-enclosed seas (SES)		1.12	2.35	3.28	*22,23*
4. Coastal Boundary Systems (CBS)		6.29	10.64	28.02	*22,24-26, 29*
5. Eastern Boundary Upwelling Ecosystems (EBUE)		1.80	6.97	19.21	*22,26,27*
6. Subtropical gyres (STG)		40.55	21.20	8.26	*22,24-26,29*
7. Deep Ocean (DO)***		N/A	N/A	N/A	*22-29*
8. Arctic and Antarctic System - Chapter 28		17.04	6.54	0.53	*23,24,25, 26*

* Based on Field et al. (1998)

** Average fish catches 1970-2006 Based on FAO

*** Not calculated (<0.5%)

Table 30-2: Regional changes in sea surface temperature (SST) over the past 50 years for ocean sub-regions specified in Figure 30-1. A linear regression was fitted to all 1x1 degree monthly SST data extracted from the HadISST 1.1 data set (Rayner et al., 2003) for the period of 1950 to 2009 for each ocean sub-region. The Table includes the slope of the regression (ºC.decade^{-1}), p value of the slope being different to zero, Linear Change Over 50 Years (slope of linear regression multiplied by 5 to obtain the average change over 50 years, and the difference between the mean temperature (1950-1959) from the mean temperature 50 years later (2000-2009). The latter may be different to the linear change over 50 years if there is significant long-term variability around the trend line. The last column compares the linear trend with that calculated between the two means with significant deviations (<0.8 and > 1.2) shown in red. P values that exceed 0.05 are also shown in red.

Region	Sub-region	oC/Decade	p Value	Linear Change Over 50 Years (1955-2005)	Mean (2000-2009) - Mean (1950-1959)	Index of Variability
1. High Latitude Spring Bloom Systems (HLSBS)						
	Indian Ocean	0.09	0.00	0.43	0.40	0.92
	North Atlantic	0.79	0.00	3.97	2.49	0.63
	South Atlantic	0.06	0.10	0.32	0.33	1.04
	North Pacific (west)	0.53	0.00	2.65	2.24	0.84
	North Pacific (east)	1.27	0.00	6.34	5.36	0.84
	Total North Pacific	0.92	0.00	4.62	3.90	0.84
	South Pacific (west)	0.02	0.65	0.08	0.12	1.43
	South Pacific (East)	0.03	0.40	0.15	0.25	1.60
	Total South Pacific	0.03	0.47	0.13	0.21	1.56
2. Equatorial Upwelling Systems (EUS)						
	Atlantic equatorial upwelling	0.09	0.00	0.45	0.49	1.09
	Pacific equatorial upwelling	0.07	0.00	0.35	0.24	0.67
3. Semi-Enclosed Seas (SES)						
	Arabian Gulf	0.10	0.30	0.50	0.45	0.91
	Baltic Sea	0.46	0.13	2.28	3.15	1.39
	Black Sea	0.05	0.68	0.26	0.54	2.04
	Mediterranean Sea	0.08	0.32	0.42	0.41	0.98
	Red Sea	0.07	0.14	0.35	0.36	1.03

4. Coastal Boundary Systems (CBS)						
	Western Atlantic	0.12	0.00	0.61	0.62	1.02
	GOM/Caribbean	0.02	0.50	0.12	0.10	0.81
	Western Indian ocean	0.10	0.00	0.50	0.49	0.98
	Eastern Indian Ocean	0.09	0.00	0.46	0.40	0.86
	E Indian/SE Asia/W Pacific	0.13	0.00	0.67	0.56	0.84
5. Eastern Boundary Upwelling Ecosystems (EBUE)						
	Benguela current	0.03	0.44	0.16	0.38	2.38
	California current	0.12	0.01	0.61	0.20	0.33
	Canary current	0.09	0.01	0.45	0.42	0.94
	Humboldt current	0.06	0.21	0.30	0.09	0.31
6. Subtropical Gyres						
	Indian ocean	0.11	0.00	0.56	0.53	0.94
	North Atlantic	0.05	0.28	0.23	0.21	0.92
	South Atlantic	0.08	0.02	0.42	0.47	1.14
	North Pacific (west)	0.07	0.02	0.36	0.34	0.96
	North Pacific (east)	0.04	0.13	0.21	0.14	0.66
	Total North Pacific	0.06	0.05	0.28	0.23	0.84
	South Pacific (west)	0.08	0.00	0.38	0.39	1.04
	South Pacific (East)	0.06	0.05	0.28	0.29	1.06
	Total South Pacific	0.06	0.03	0.30	0.32	1.05
7. Coral Reef Provinces (Figure 30.3)						
	Caribbean & Gulf of Mexico	0.02	0.38	0.12	0.13	1.11
	Coral Triangle & SE Asia	0.13	0.00	0.65	0.55	0.84
	Eastern Indian Ocean	0.10	0.00	0.49	0.43	0.88
	Western Indian Ocean	0.10	0.00	0.50	0.48	0.97
	Eastern Pacific Ocean	0.09	0.00	0.47	0.24	0.52
	Western Pacific Ocean	0.07	0.00	0.36	0.39	1.07

8. Basin Scale						
	North Atlantic combined	0.52	0.00	2.62	1.67	0.09
	South Atlantic combined	0.07	0.04	0.37	0.41	0.04
	Atlantic Ocean Basin	0.30	0.00	1.51	1.05	0.03
	North Pacific total	0.38	0.00	1.89	1.59	0.07
	South Pacific total	0.05	0.11	0.24	0.28	0.03
	Pacific Ocean Basin	0.20	0.00	1.01	0.88	0.02
	Indian Ocean basin	0.11	0.00	0.56	0.53	0.94

Table 30-3: CMIP-5 models used to create the Chapter 30 RCP 2.6, 4.5, 6.0 and 8.5 SST ensembles. All models indicated were used in both the ensemble SSTs as well as the production of the DHMs, with the exception of 2 model outputs, denoted by a *. These two models were included in the ensembles but not in the production of the DHMs due to issues with the development of an appropriate Maximum Monthly Mean (MMM) climatology.

CMIP-5 Model	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
ACCESS1-0		1		1
ACCESS1-3		1		1
BCC-CSM1-1	1	1	1	1
CanESM2	1	1		1
CMCC-CM		1		1
CMCC-CMS		1		1
CNRM-CM5	1	1		1
CSIRO-Mk3-6-0	1	1	1	1
EC-EARTH	*	1		1
FIO-ESM	1	1	1	1
GFDL-CM3	1	1	1	1
GFDL-ESM2G	1	1	1	1
GFDL-ESM2M	1	1		1
GISS-E2-R-p1	1	1	1	1
GISS-E2-R-p2	1	1	1	1
GISS-E2-R-p3	1	1	1	1
HadGEM2-AO	1	1	1	1
HadGEM2-CC		1		1
HadGEM2-ES	1	1	1	1
INMCM4		1		1
IPSL-CM5A-LR	1	1	*	1
IPSL-CM5A-MR	1	1		1
MPI-ESM-LR	1	1		1
MPI-ESM-MR	1	1		1
CESM1-BGC		1		1
CESM1-CAM5	1	1	1	1
NorESM1-M	1	1	1	1
NorESM1-ME	1	1	1	1
Number of models	**20+1***	**28**	**13+1***	**28**

Table 30-4: Projected changes in sea surface temperature (SST, ºC) over the next 90 years for Ocean sub-regions (Figure 30-1) using model runs from the Coupled Model Intercomparison Project Phase 5 (CMIP-5, http://cmip-pcmdi.llnl.gov/cmip5/). Runs were divided up into their respective Representative Concentration Pathways (RCP) to form four groups: RCP2.6, RCP4.5, RCP6.0 and RCP8.5. The CMIP-5 models that were used in this analysis are listed in Table 30.3. For each region, a linear regression was fitted to all 1x1 degree monthly SST data extracted from the models for each of three periods; 2010-2039, 2040-2069 and 2070-2099. The average change in SST was calculated by multiplying the slope of each linear regression by 360 (months) to derive the average change over each successive 30 year period. The table is divided into two sections, "Near-term (2010-2039)" – the average change in SST over the next 30 years, and "Long-term (2010-2099)" – the total change from 2010-2099, which was calculated by adding the average change of the three 30 year periods from 2010 to 2099. This is a simplified method to account for slight non-linearity in SST change over the 90 year period.

Region	Sub-region	Near-term (2010-2039)				Long-term (2010-2099)				Diff RCP8.5 - RCP2.6
		RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5	
1. High Latitude Spring Bloom Systems (HLSBS)										
	Indian Ocean	0.13	0.29	0.18	0.41	-0.16	0.49	0.83	2.01	2.17
	North Atlantic	0.31	0.56	0.52	0.65	0.54	1.54	1.95	3.02	2.48
	South Atlantic	0.17	0.36	0.20	0.45	-0.09	0.67	0.88	2.26	2.36
	North Pacific (west)	0.79	0.96	0.91	1.17	1.46	2.47	3.07	4.84	3.38
	North Pacific (east)	0.79	0.81	0.93	1.06	1.31	2.17	2.96	4.39	3.08
	Total North Pacific	0.79	0.88	0.92	1.11	1.35	2.31	3.01	4.60	3.25
	South Pacific (west)	0.17	0.40	0.25	0.50	-0.16	0.63	0.85	2.37	2.53
	South Pacific (East)	0.12	0.23	0.13	0.35	-0.09	0.45	0.75	1.70	1.79
	Total South Pacific	0.14	0.28	0.17	0.40	-0.12	0.51	0.78	1.91	2.03
2. Equatorial Upwelling Systems (EUS)										
	Atlantic equatorial upwelling	0.43	0.58	0.49	0.81	0.46	1.19	1.61	3.03	2.56
	Pacific equatorial upwelling	0.35	0.55	0.54	0.77	0.43	1.22	1.75	3.01	2.57
3. Semi-Enclosed Seas (SES)										
	Arabian Gulf	0.82	0.97	0.89	1.20	1.30	2.39	2.96	4.26	2.96
	Baltic Sea	0.73	1.24	0.92	1.20	1.32	2.74	3.06	4.37	3.05
	Black Sea	0.74	1.01	0.86	1.24	1.37	2.61	3.16	4.19	2.82
	Mediterranean Sea	0.72	0.87	0.84	1.09	1.37	2.10	2.82	4.08	2.70
	Red Sea	0.56	0.72	0.71	0.93	0.88	1.65	2.39	3.45	2.57

4. Coastal Boundary Systems (CBS)										
	Western Atlantic	0.34	0.40	0.45	0.62	0.23	0.81	1.33	2.44	2.21
	GOM/Caribbean	0.50	0.67	0.64	0.85	0.74	1.53	1.97	3.23	2.49
	Western Indian ocean	0.46	0.59	0.56	0.85	0.63	1.39	1.95	3.32	2.69
	Eastern Indian Ocean	0.34	0.57	0.46	0.69	0.38	1.22	1.59	2.80	2.42
	E Indian/SE Asia/W Pacific	0.48	0.66	0.57	0.82	0.66	1.47	1.89	3.12	2.46
5. Eastern Boundary Upwelling Ecosystems (EBUE)										
	Benguela current	0.30	0.43	0.45	0.71	0.07	0.70	1.41	2.52	2.45
	California current	0.62	0.71	0.84	0.93	1.02	1.86	2.46	3.51	2.49
	Canary current	0.55	0.62	0.58	0.82	0.97	1.30	1.83	3.18	2.21
	Humboldt current	0.22	0.43	0.34	0.60	0.11	0.91	1.22	2.58	2.47
6. Subtropical Gyres										
	Indian ocean	0.30	0.44	0.37	0.63	0.19	0.89	1.35	2.62	2.43
	North Atlantic	0.49	0.66	0.60	0.85	0.87	1.62	1.98	3.30	2.43
	South Atlantic	0.25	0.33	0.33	0.55	0.03	0.58	1.03	2.20	2.18
	North Pacific (west)	0.54	0.70	0.64	0.90	0.84	1.62	2.08	3.39	2.55
	North Pacific (east)	0.56	0.66	0.71	0.91	0.90	1.56	1.50	3.44	2.54
	Total North Pacific	0.55	0.68	0.68	0.90	0.87	1.58	2.09	3.42	2.55
	South Pacific (west)	0.31	0.44	0.34	0.62	0.12	0.88	1.19	2.56	2.44
	South Pacific (East)	0.17	0.27	0.21	0.45	-0.03	0.52	0.89	1.90	1.93
	Total South Pacific	0.20	0.31	0.24	0.49	0.00	0.60	0.96	2.05	2.05
7. Coral Reef Provinces (Figure 30.3)										
	Caribbean & Gulf of Mexico	0.48	0.64	0.61	0.83	0.68	1.43	1.87	3.14	2.46
	Coral Triangle & SE Asia	0.42	0.61	0.52	0.76	0.58	1.35	1.75	2.95	2.37
	Eastern Indian Ocean	0.32	0.56	0.46	0.67	0.37	1.18	1.59	2.76	2.40
	Western Indian Ocean	0.39	0.51	0.50	0.77	0.43	1.18	1.71	2.97	2.54
	Eastern Pacific Ocean	0.46	0.64	0.64	0.83	0.63	1.44	1.99	3.23	2.60
	Western Pacific Ocean	0.35	0.48	0.40	0.68	0.30	1.02	1.39	2.66	2.35

8. Basin Scale changes										
	North Atlantic combined	0.37	0.60	0.55	0.72	0.66	1.57	1.96	3.12	2.46
	South Atlantic combined	0.21	0.35	0.27	0.51	-0.03	0.62	0.76	2.23	2.26
	Atlantic Ocean Basin	0.32	0.50	0.44	0.65	0.38	1.17	1.54	2.78	2.40
	North Pacific total	0.64	0.75	0.77	0.98	1.06	1.85	2.43	3.86	2.80
	South Pacific total	0.18	0.30	0.21	0.45	-0.04	0.56	0.89	2.00	2.04
	Pacific Ocean Basin	0.41	0.54	0.51	0.73	0.52	1.23	1.70	2.97	2.45
	Indian Ocean Basin	0.30	0.44	0.37	0.63	0.19	0.89	1.35	2.62	2.43

Table 30-5: Examples of priority adaptation options and supporting policies to assist Pacific Island countries and territories to minimize the threats of climate change to the socio-economic benefits derived from fisheries and aquaculture, and to maximize the opportunities. These measures are classified as 'win-win' (W-W) adaptations, which address other drivers of the sector in the short term and climate change in the long term, or 'lose-win' (L-W) adaptations, where benefits exceed costs in the short term but accrue under longer-term climate change (Modified from *Bell et al*. 2013a).

<table>
<tr><th>Adaptation options</th><th>Supporting policies</th></tr>
<tr><td>Economic development
Full implementation of the vessel day scheme (VDS) to control fishing effort by the Parties to the Nauru Agreement[a] (W-W).</td><td rowspan="5">• Strengthen national capacity to administer VDS.
• Adjust national tuna management plans and marketing strategies to provide flexible arrangements to buy and sell tuna.
• Include implications of climate change in management objectives of the WCPFC.
• Apply national management measures to address climate change effects for sub-regional concentrations of tuna in archipelagic waters beyond WCPFC's mandate.
• Require all industrial tuna vessels to provide operational-level catch and effort data to improve models for projecting redistribution of tuna stocks during climate change.</td></tr>
<tr><td>Diversify sources of fish for canneries and maintain trade preferences (W-W).</td></tr>
<tr><td>Continued conservation and management measures for all species of tuna to maintain stocks at healthy levels and maximize their resilience to climate change (W-W).</td></tr>
<tr><td>Energy efficiency programmes to assist fleets to cope with oil price rises, minimise CO_2 emissions, and reduce costs of fishing further afield as tuna move east (W-W).</td></tr>
<tr><td>Pan-Pacific tuna management through a merger of the Western and Central Pacific Fisheries Commission (WCPFC) and Inter-American Tropical Tuna Commission to co-ordinate management measures across the entire tropical Pacific (L-W).</td></tr>
<tr><td>Food security and livelihoods
Manage catchment vegetation to reduce transfer of sediments and nutrients to rivers and coasts to reduce damage to freshwater fish habitats, and coral reefs, mangroves and seagrasses supporting coastal fisheries (W-W).</td><td rowspan="8">• Strengthen governance for sustainable use of coastal fish habitats by: (1) building national capacity to understand the threats of climate change; (2) empowering communities to manage fish habitats; and (3) changing agriculture, forestry and mining practices to prevent sedimentation and pollution.
• Minimise barriers to landward migration of coastal habitats during development of strategies to assist other sectors to respond to climate change.
• Apply 'primary fisheries management' to stocks of coastal fish and shellfish to maintain their potential for replenishment.
• Allocate the necessary quantities of tuna from total national catches to increase access to fish for both urban and coastal populations.
• Dedicate a proportion of the revenue from fishing licences to improve access to tuna for food security.
• Include inshore FADs as part of national infrastructure for food security, and undertake regular maintenance and replacement of FADs.
• Provide incentives for aquaculture enterprises to assess risks to infrastructure so that farming operations and facilities can be 'climate-proofed' and relocated if necessary.</td></tr>
<tr><td>Foster the care of coral reefs, mangroves and seagrasses by preventing pollution, managing waste and eliminating direct damage to these coastal fish habitats (W-W).</td></tr>
<tr><td>Provide for migration of fish habitats by: (1) prohibiting construction adjacent to mangroves and seagrasses and installing culverts beneath roads to help plants colonise landward areas as sea level rises; and (2) allowing floodplains to expand as rainfall increases (L-W).</td></tr>
<tr><td>Sustain and diversify catches of coral reef fish to maintain the replenishment potential of all stocks (L-W).</td></tr>
<tr><td>Increase access to tuna and by-catch caught by industrial fleets through storing and selling these fish at major ports to provide inexpensive fish for rapidly growing urban populations (W-W).</td></tr>
<tr><td>Install fish aggregating devices (FADs) close to the coast to improve access to tuna and other large pelagic fish for rural communities as human populations increase and coral reef fish decline (W-W).</td></tr>
<tr><td>Improve simple post-harvest methods to extend the shelf life of fish when good catches are made (W-W).</td></tr>
<tr><td>Relocate pearl farming operations to deeper water and sites closer to coral reefs and seagrass/algal areas where water temperatures and aragonite saturation levels are likely to be more suitable for growth and survival of pearl oysters, and formation of high-quality pearls (L-W).</td></tr>
</table>

a = The Parties to the Nauru Agreement (PNA) are Palau, Federated States of Micronesia, Papua New Guinea, Solomon Islands, Marshall Islands, Nauru, Kiribati and Tuvalu.

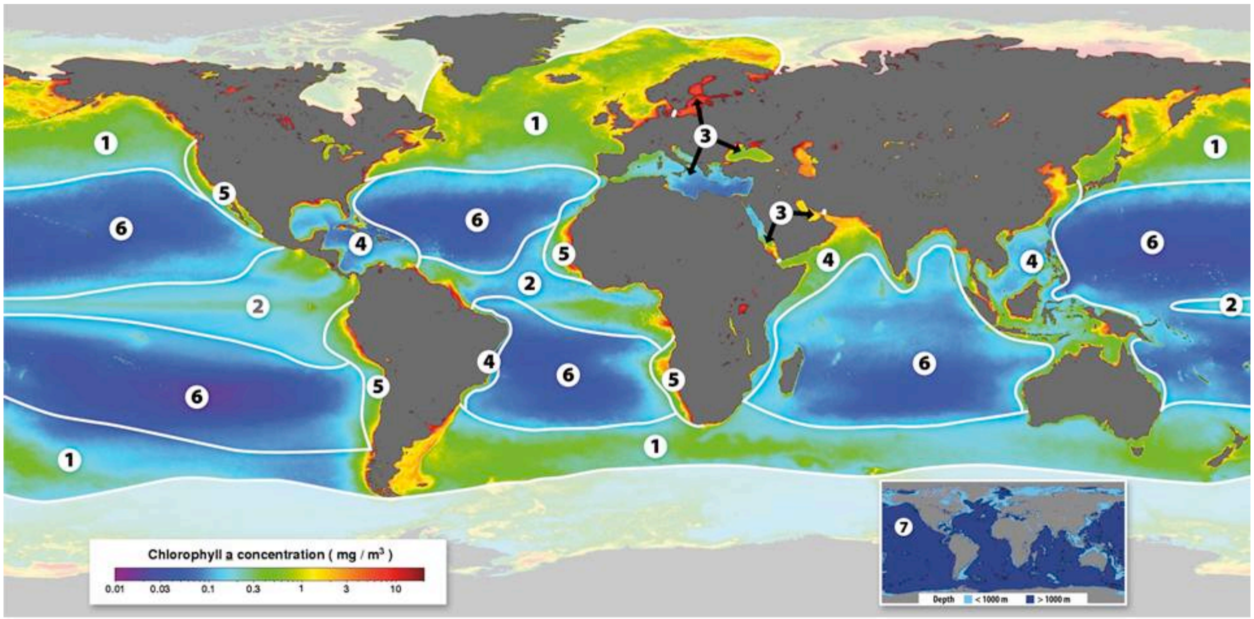
Table 30-6: Key risks and vulnerabilities, as well as ramifications, adaptation options and frameworks for decision-making within a number of areas discussed in chapter 30. Symbols are as follows: T = sea temperature; UW = upwelling; OA = ocean acidification; NU = nutrient concentration; IC = ice cover; SS = storm strength, SLR = sea level rise (□ = Increased; □ = decreased; italics = uncertain). Acronyms are: CBD (Convention on Biological Diversity), CTI (Coral Triangle Initiative), GEF (Global Environment Facility), IHO (International Hydrographic Organization), ILO (International Labour Organisation), IOM (International Organisation of Migration), ISPS (International Ship and Port Facility Security), LOSC (1982 Law of the Sea Convention), MARPOL (International Convention for the Prevention of Pollution From Ships), PACC (Pacific Adaptation to Climate Change Project), PEMSEA (Partnerships in Environmental Management for the Seas of East Asia), RFMO (Regional Fisheries Management Organisations), SPREP (Secretariat of the Pacific Regional Environment Programme), UNCLOS (United Nations Convention on the Law of the Sea), UNHCR (United Nations High Commissioner for Refugees), and WHO (World Health Organisation).

Primary driver(s)	**Biophysical change projected**	**Key risks and vulnerabilities**	**Ramifications**	**Adaptation options**	**Policy frameworks and initiatives (examples)**	**Key References**
↑T, ↑UW, ↑*OA*	Changing primary productivity	Reduced fisheries production reduces important sources of income to some countries while others may see increase (e.g. as tuna stocks migrate eastwards in the Pacific with warming).	Reduced national income, increased unemployment, plus increase in poverty. Potential increase in disputes over national ownership of key fishery resources	Increased international cooperation over key fisheries. Improved understanding of linkages between ocean productivity, recruitment and fisheries stock levels. Implementation of the regional 'vessel day scheme', support industry as costs rise, stock characteristics change.	LOSC, PEMSEA, CTI, RFMO agreements	Tsamenyi and Hanich (2012); Bell et al. 2012, 2013; Section 30.6.1.1
↑T, ↑*OA*	Ecosystem regime shifts (e.g. coral to algal reefs; structural shifts in phytoplankton community)	Reduced fisheries production as coastal habitats and ecosystems such as coral reefs and other coastal ecosystems degrade.	Decreased food and employment security and human migration away from coastal zone	Strengthen coastal zone management to reduce contributing stressors (e.g. coastal pollution, over-harvesting and physical damage to coastal resources). Promote blue carbon initiatives - restoration of coastal habitats such as mangroves, salt marshes and seagrass beds.	PEMSEA, CTI, PACC, MARPOL, UNHCR, CBD, IOM, GEF, ILO	Bell et al. 2012, 2013; Section 30.6.1.1
		Tourist appeal of coastal assets decreases as ecosystems change to less 'desirable' state reducing income to some countries.	Increased levels of coastal poverty in some countries as tourist income decreases.	As above, strengthen coastal zone management and reduce additional stressors on tourist sites; implement education programs and awareness among visitors. Diversify tourist activities to accommodate change in condition of local ecosystems.	CBD, PEMSEA, CTI, PACC, UNHCR, MARPOL	Kenchington and Warner (2012)
		Increased risk of some diseases (e.g. ciguatera may increase as temperatures increase shift and ecosystems shift away from coral dominance)	Increased disease and mortality; decreases in coastal food resources and fisheries income.	Increased monitoring and education surrounding key risks (e.g. ciguatera); develop alternate fisheries and income for periods when disease incidence increases.	National policy strategies as well as and regional cooperation needed	

Primary driver(s)	Biophysical change projected	Key risks and vulnerabilities	Ramifications	Adaptation options	Policy frameworks and initiatives (examples)	Key References
		Increased poverty and dislocation of coastal people (particularly in the tropics) as coastal resources such as fisheries degrade.	Increased population pressure on migration destinations (e.g. large regional cities), and reduced freedom to navigate in some areas (as criminal activity increases).	Develop alternative industries and income for affected coastal people. Strengthen coastal security both nationally and across regions. Increase cooperation over criminal activities.	LOSC, PEMSEA, CTI, ISPS, IMO, Bali Process on Transnational Crime ASEAN Mutual legal Assistance treaty and bilateral extradition and MLA agreements	Rahman (2012), Kaye (2012),
↑T	Migration of organisms and ecosystems to higher latitudes.	Sudden reorganization of commercial fisheries due arrival of novel organisms and ecological regime shifts.	Social and economic disruption over short periods of time.	Increased international cooperation and improve understanding of regime changes; provide increased monitoring of physical and biological variables; include related uncertainties into fisheries management; support industry as costs rise, stock characteristics change. change.	LOSC, CBD, RFMO agreements	
		Increased risks from pests and fouling as new species arrive at higher latitudes.	Increased damage to coastal ecosystems, aquaculture and fisheries. Income loss and increased costs associated with responding.	Increase monitoring of changes to community and ecosystem structure; provide assistance to industry impacted by pest and fouling organisms; control contributing factors such as the transport of invading organisms on ships hulls and in ballast water.	IMO, BWM, Anti Fouling Convention	
		Threats to human health increase due to the arrival of new pathogens at higher latitudes.	Increased disease and mortality in some coastal communities.	Reduce exposure through increased monitoring and education	UNICEF, WHO, IHOs, and national governments.	Myers and Patz (2009)
↑T, ↑NU, ↑*OA*	Increased incidence of harmful algal blooms (HABs).	Increased threats to ecosystems, fisheries and human health.	Reduced food and greater incidence of disease among some coastal communities.	Reduce nutrient run-off and other contributing issues; improve understanding of how related variables facilitate increased incidence of HABs.	CTI, PEMSEA, MARPOL	
↑T	Increased precipitation as a result of intensified hydrological cycle in some coastal areas	Increased freshwater, sediment and nutrients flow into coastal areas.	Increasing damage to coastal reef systems with ecological regime shifts in many cases.	Improve management of catchment and coastal processes; expand riparian vegetation along creeks and rivers; improve agricultural retention of soils and nutrients.	CTI, PEMSEA, SPREP	

Primary driver(s)	Biophysical change projected	Key risks and vulnerabilities	Ramifications	Adaptation options	Policy frameworks and initiatives (examples)	Key References
↑T	Changing weather patterns (local climates, storm intensity)	Increased risk of damage to infrastructure such as that involved in shipping, and oil and gas exploration and extraction.	Increased damage and associated costs	Adjust infrastructure specifications for new conditions and developed more advanced monitoring and warning systems.	IMO	
↑SLR, ↑*SS*	Increased wave exposure of coastal areas	Exposure of coastal infrastructure and communities to damage and inundation	Increased costs to human towns and settlements, numbers of displaced people and human migration.	Develop integrated coastal plans that consider SLR in planning and decision making; increase understanding of the issues through education.	UNICEF, IHOs, and national governments.	Warner (2010)
		Inundation of coastal aquifers reduces water supplies and decreased coastal agricultural productivity.	Reduced food and water security leads to increased coastal poverty, reduced food security, and migration.	Assist communities to find alternatives for food and water, or assist in relocation from vulnerable areas.	UNICEF, IHOs, and national governments.	Warner (2010) CHAPTER 5 linkages
↑SLR	High tide mark moves inland, especially in low-lying countries.	UNCLOS defined limits of maritime jurisdiction will contract as national baselines shift inland. Potential uncertainty increases in some areas with respect to the international boundaries to maritime jurisdiction.	Lack of clarity increases as do disputes over maritime limits and maritime jurisdiction. Some nations at risk of major losses to their territorial waters.	Seek resolution of 'shifting national baselines' issue (retreat and redefinition, stabilization, or fixation of EEZ and other currently defined maritime jurisdiction limits.	LOSC, UNCLOS	Schofield and Arsana (2012); Warner and Schofield (2012)
↑T, ↓IC	Loss of summer sea ice	Access to northern coasts of Canada, USA and Russia increases security concerns.	Potential for increased tension on different interpretations.	Seek early resolution of areas in dispute currently and in the future.	LOSC, UNCLOS	WGII Chapter 28
		New resources become available as ice retreats, increasing vulnerability of international borders in some cases.	Tensions over maritime claims and ownership of resources.	International agreements need to be sort.	LOSC, UNCLOS	

A



B

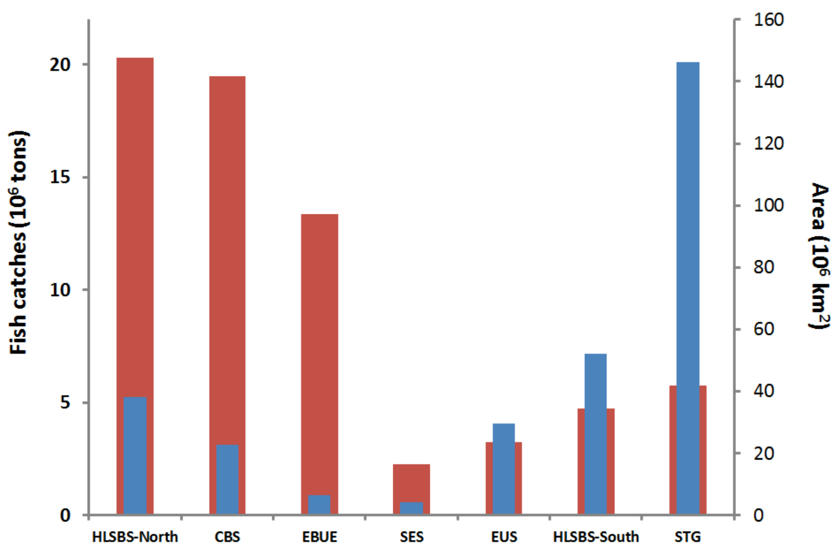


Figure 30-1: A. The world's non-polar oceans have been separated into seven major sub-regions, with polar oceans being excluded due to treatment elsewhere (Ch28). The chlorophyll concentration averaged over the period from Sep 1997 – 30 Nov 2010 (NASA) is also shown. Together with key oceanographic features, primary production was the basis for separating the ocean into the sub-regions shown. The map insert shows the distribution of Deep Sea habitat (>1000 m; Bathypelagic and Abyssopelagic habitats combined). Numbers refer to: 1 = High Latitude Spring Bloom Systems (HLSBS), 2 = Equatorial Upwelling (EUS), 3 = Semi-enclosed seas (SES), 4 = Coastal Boundary Systems (CBS), 5 = Eastern Boundary Upwelling Ecosystems (EBUE), 6 = Subtropical gyres (STG), and 7 = Deep sea (>1000 m). B. relationship between fish catch and areas for Ocean sub-regions shown in A. Red columns: average fish catch (millions tons yr^{-1}) for the period 1970-2006. Blue columns: area (millions km^2).

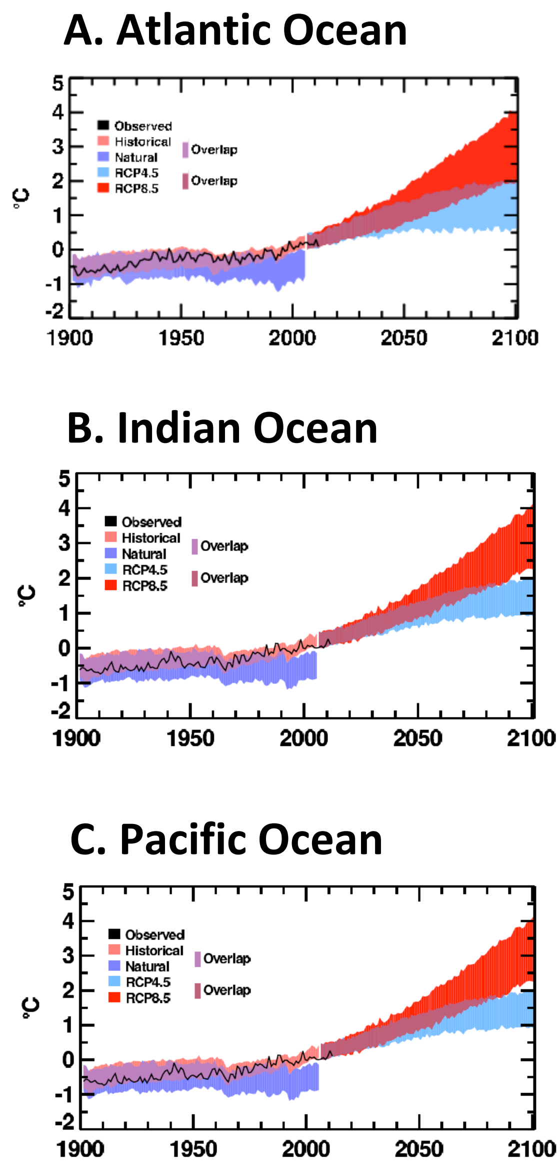


Figure 30-2: Observed and simulated variations in past and projected future annual average sea surface temperature over various oceanic regions. The black line shows estimates from HadISST1 observational measurements. Shading denotes the 5-95 percentile range of climate model simulations driven with "historical" changes in anthropogenic and natural drivers (62 simulations), historical changes in "natural" drivers only (25), the "RCP4.5" emissions scenario (62), and the "RCP8.5" (62). Data are anomalies from the 1986-2006 average of the HadISST1 data (for the HadISST1 time series) or of the corresponding historical all-forcing simulations. Further details are given in Box 21-3.

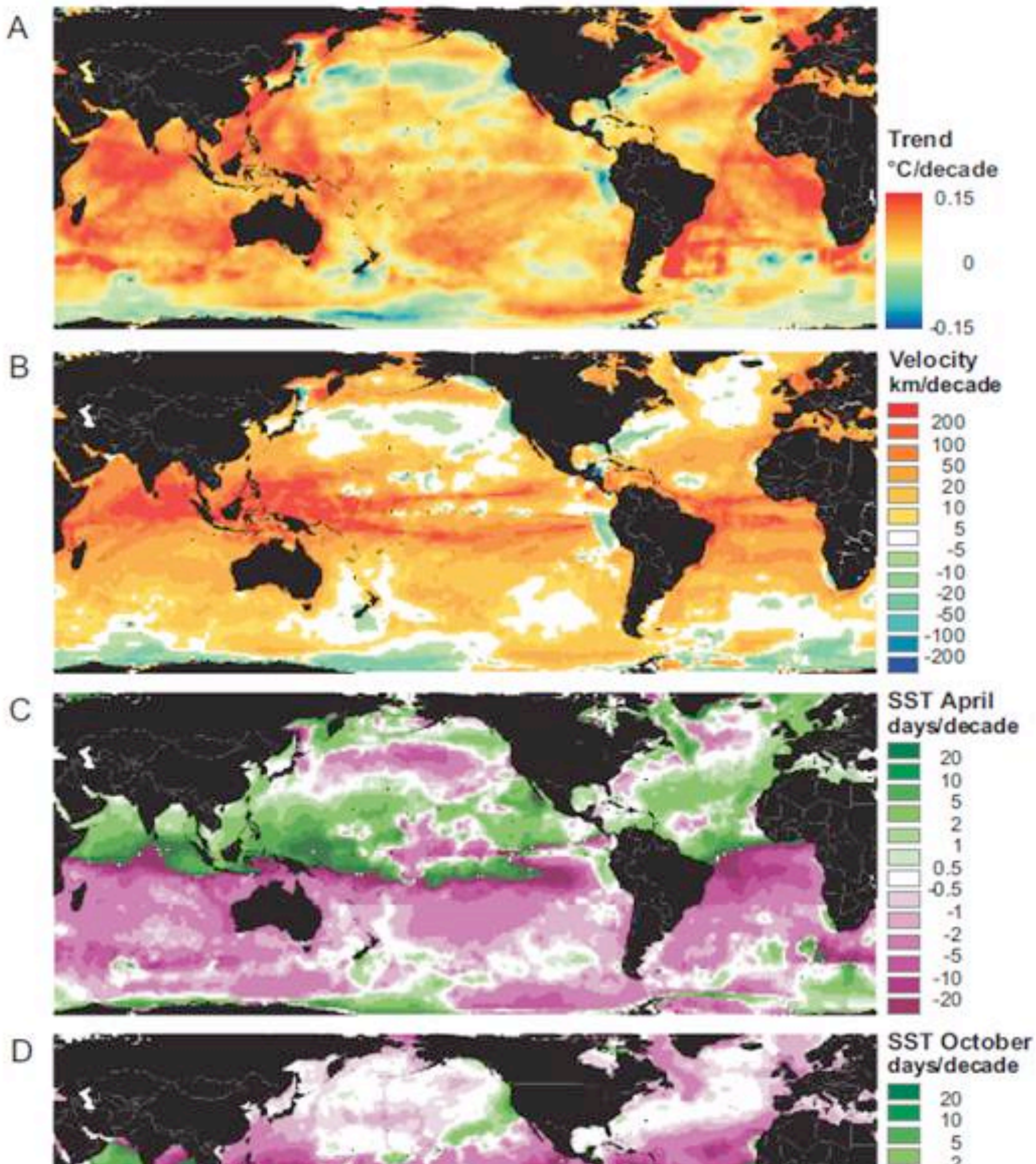


Figure 30-3: Analysis of data from Hadley Centre (HadISST 1.1, [*Rayner et al*., 2003]) for different ocean sub-regions. A. Rate of change in sea surface temperature over the past 30 years (°C. decade^{-1}). B. Velocity at which isotherms are moving (km.decade^{-1}) from 1960-2009. C. Shift in seasonal changes that drive natural history events (days.decade^{-1}) for April and D. for October. E.

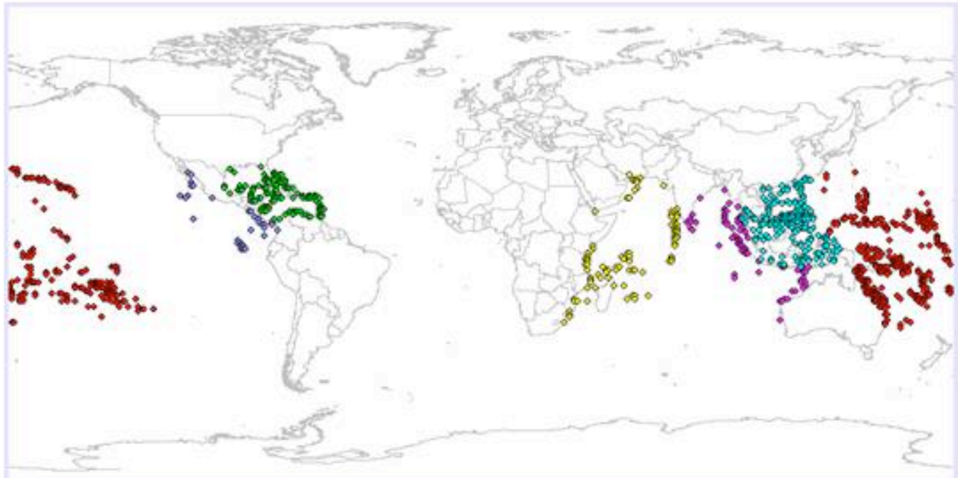


Figure 30-4: Location of coral reef grid cells used in Tables 30.2 and 30.4 as well as in Figure 30.11. Each dot is centred over a 1x1 degree grid cell within which lies at least one coral reef. The latitude and longitude of each reef is derived from data provided by the World Resources Institute's Reefs at Risk (http://www.wri.org). The six regions are as follows: Red – Western Pacific; Blue – Eastern Pacific Ocean; Green – Caribbean & Gulf of Mexico; Yellow – Western Indian Ocean; Magenta – Eastern Indian Ocean; and Cyan – Coral Triangle & SE Asia.

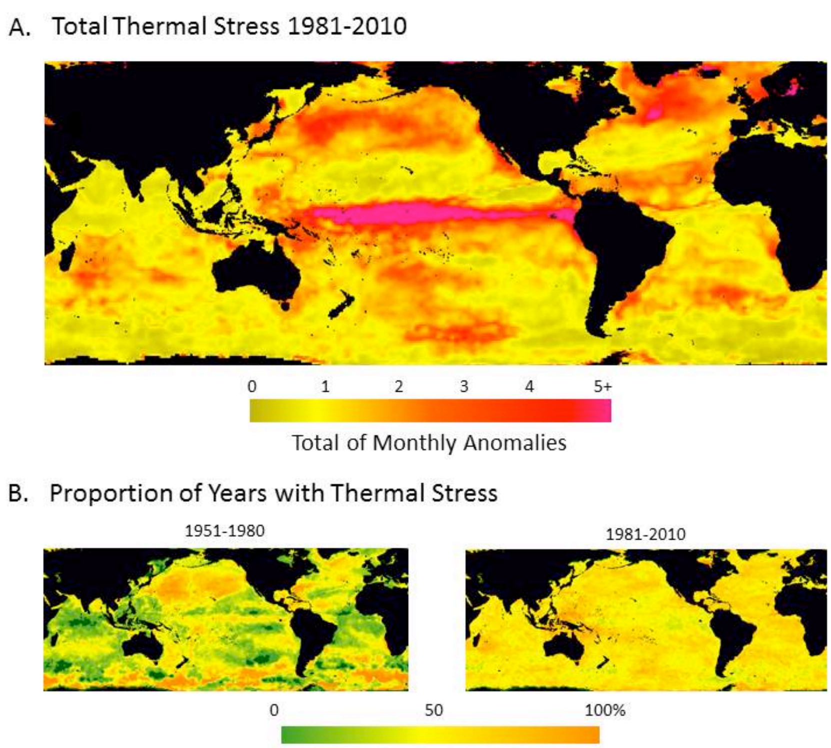


Figure 30-5: Recent changes in thermal stress calculating using HadISST 1.1 data. A monthly climatology was created by averaging the HadISST monthly SST values over the period 1985-2000 to create twelve averages, one for each month of the year. The Maximum Monthly Mean (MMM) climatology was then created by selecting the hottest month for each pixel. Anomalies were then created by subtracting this value from each SST value, but only allowing values to be recorded if they were greater than zero (Donner et al., 2007). Three measures of thermal stress change were then created: (A) Total thermal stress for the period 1981-2010, calculated by summing all monthly thermal anomalies for each grid cell. (B) Proportion of years with thermal stress, which is defined as any year that has a thermal anomaly, for the periods 1951-1980 and (C) 1981-2010.

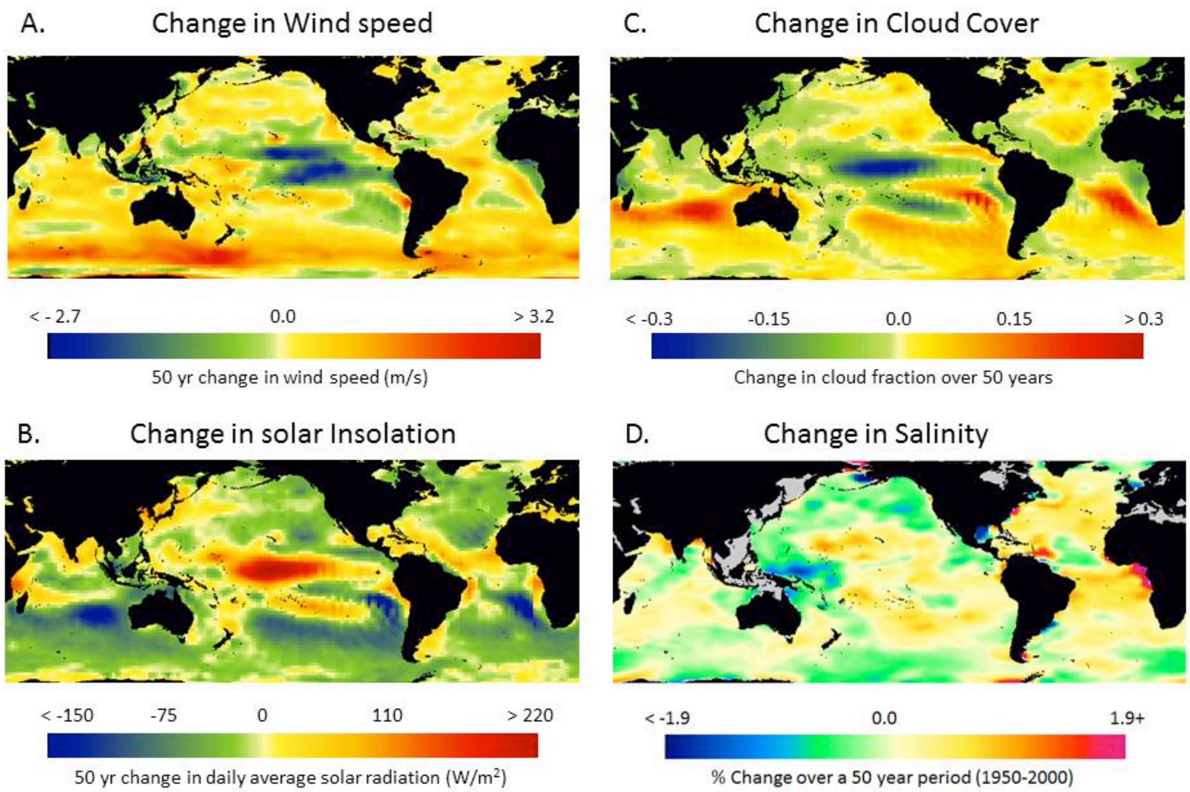


Figure 30-6: Absolute change over 50 years calculated using regression analysis of data from 1951-2010 (A) Wind Speed as the absolute change in $m.s^{-1}$; (B) Solar radiation as change at the surface of incoming solar insolation in Wm^{-2}; (C) Cloud Cover as the absolute change in total cloud fraction (i.e. If at the beginning of the period the cloud fraction was 0.6 and 0.5 at the end of the period, the change would be -0.1) using NCEP re-analyzed data (www.esrl.noaa.gov); and (D) Salinity as the percentage change from 1960-2010 [reproduced using the data of Durack and Wijffels, 2010]. Data for (A), (B) and (C) were derived from the NCEP/NCAR Reanalysis [*Kanamitsu et al*., 2002]. Monthly mean values for wind speed, total cloud cover and downward solar radiation flux (solar insolation) were obtained from http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.derived.html. At each 1x1 degree grid cell, a linear regression was calculated for each of wind, cloud and solar insolation. The slopes were then multiplied by 600 (months) to calculate the average change over a 50 year period.

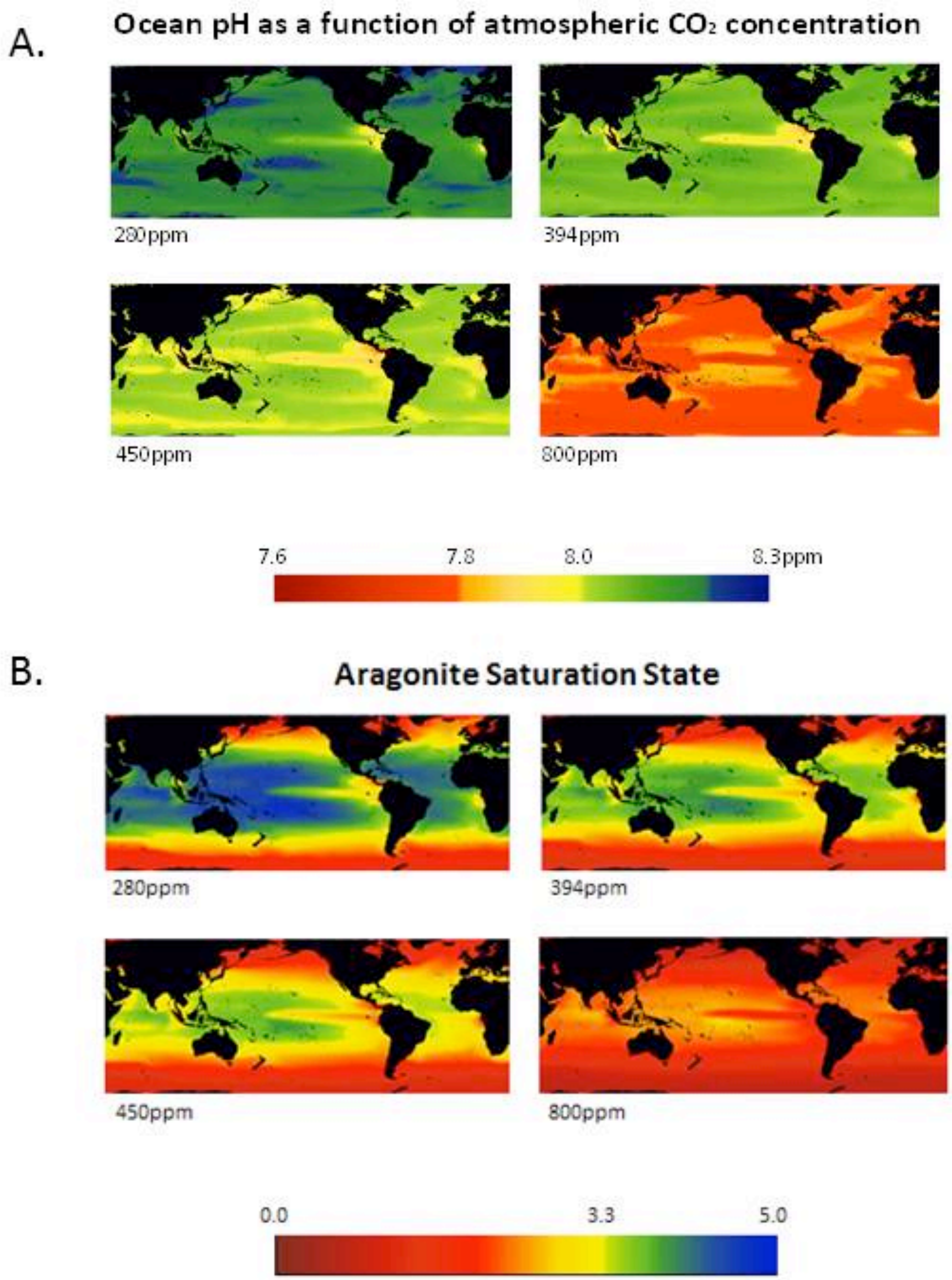


Figure 30-7: A. Surface pH and B. aragonite saturation state of the Ocean at different atmospheric CO_2 levels simulated by the University of Victoria Earth System Model. The fields of pH and aragonite saturation state are calculated from the model output of dissolved inorganic carbon concentration, alkalinity concentration, temperature, and salinity, together with the chemistry routine from the OCMIP-3 project (http://www.ipsl.jussieu.fr/OCMIP/phase3).

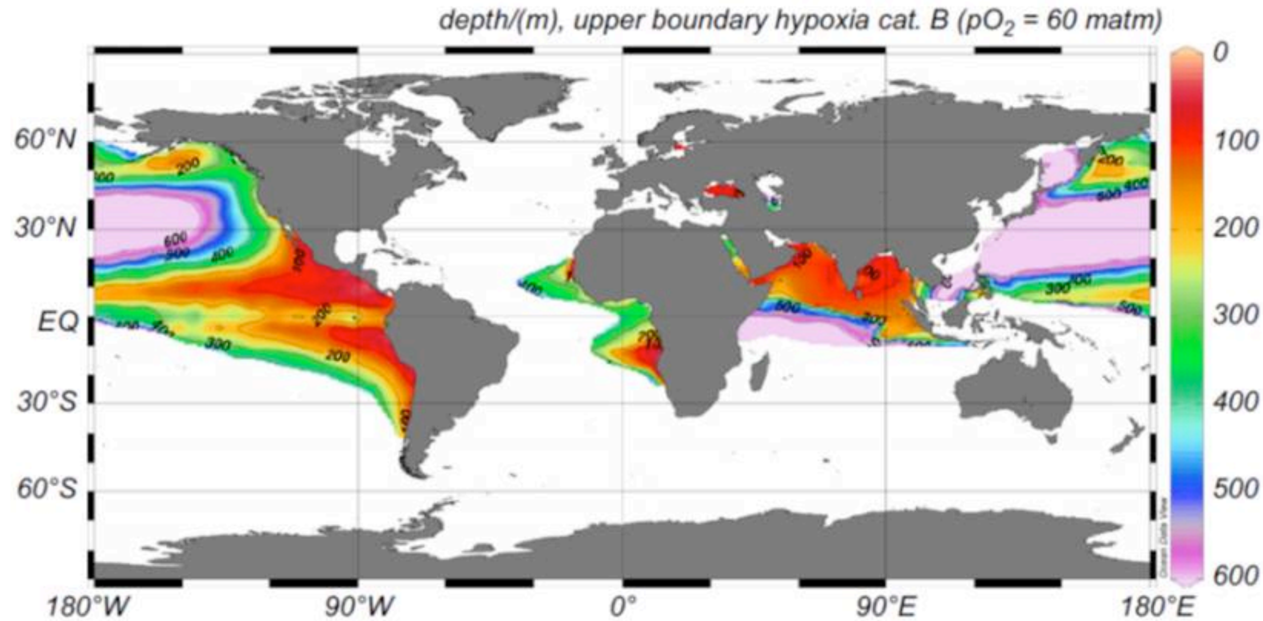


Figure 30-8: Map of the depth [*Hofmann et al*., 2011] at which a critical value of partial pressure of O_2 of 60 matm occurs which is widely accepted as threatening to marine life on continental shelves (200m depth). Conventional maps of oceanic oxygen values report simple mass properties with no temperature or depth dependence; a better rendition of the availability of O_2 to marine life is provided by the partial pressure, which includes the temperature terms. Critical sub-regions in the eastern and northern Pacific and in the northern Indian ocean stand out. In these areas quite modest upward expansion of the depth at which the critical pO_2 level occurs can have negative effects on major fish populations. Note: not all areas have been included – for example, significant hypoxia in the Gulf of Mexico is not been shown.

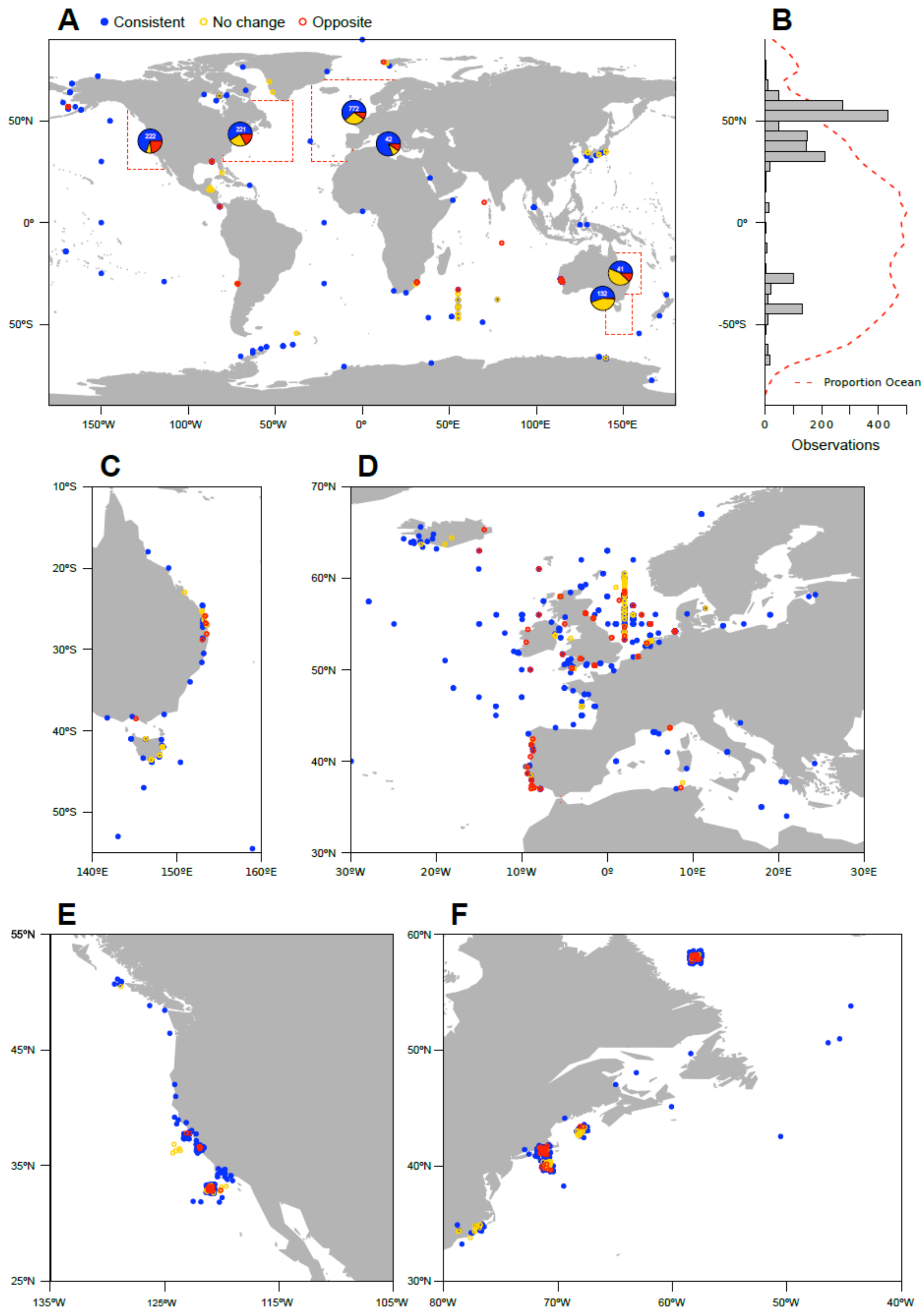


Figure 30-9: (A) 1735 observed responses to climate change from 208 single- and multi-species studies showing responses that are consistent with climate change (blue), opposite to expected (red) and are equivocal (yellow). Each circle represents the centre of a study area. Where points fall on land, it is because they are centroids of distribution that surround an island or peninsula. Pie charts show the proportions within regions bounded by red squares and in the Mediterranean; numbers indicate the total (consistent, opposite plus equivocal) observations within each region. (B) Frequency of observations by latitude. (C) South-west Pacific. (D) North-east Atlantic. (E) California Current. (F) North-west Pacific (Poloczanska et al 2013).

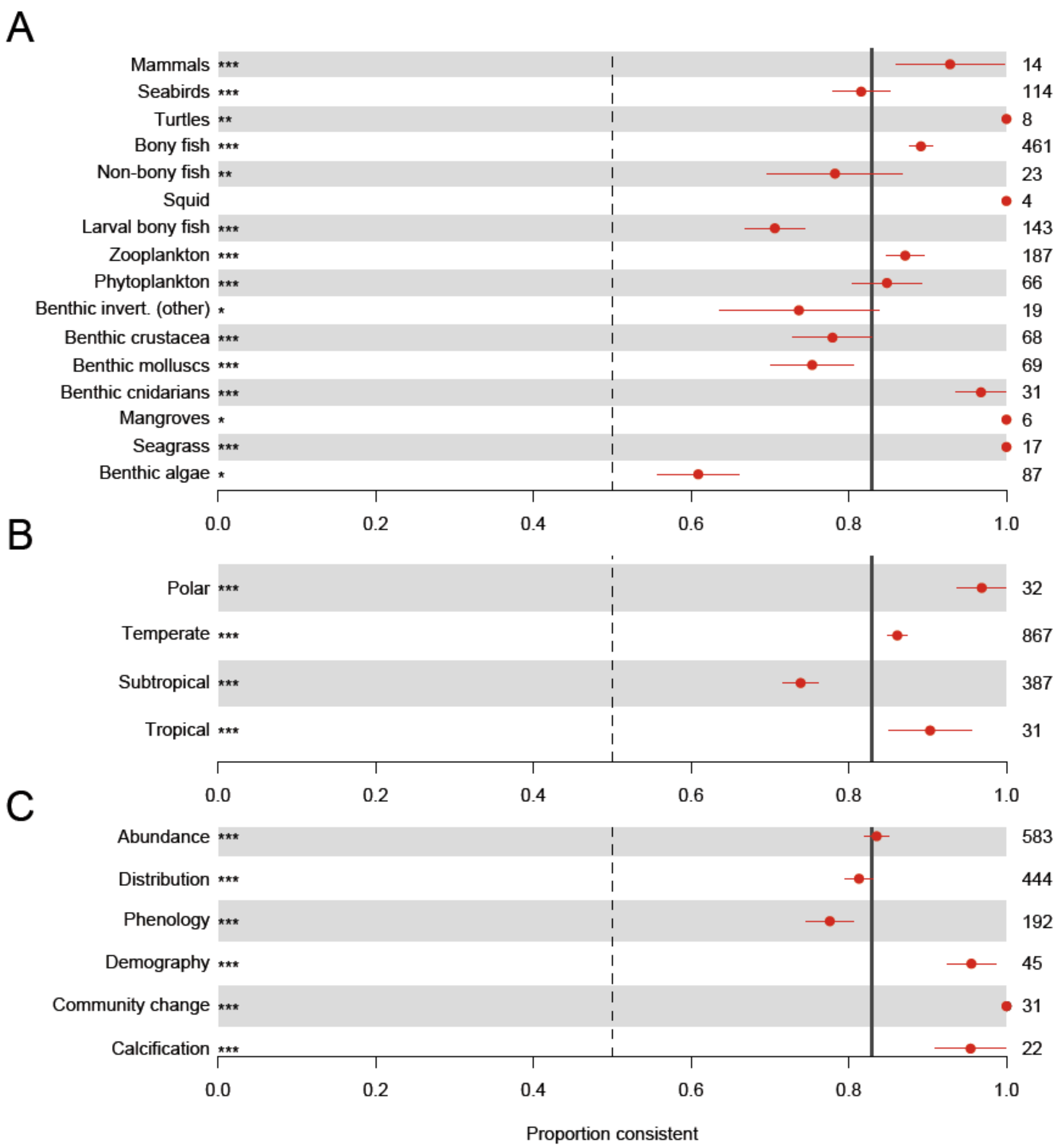


Figure 30-10: Percent of responses consistent with climate change predictions. Mean and standard error of responses by (A) taxa, (B) latitudinal region and (C) response measure show significantly higher consistency than expected from random (dashed line at 50% consistency). Solid line is the mean across all observations. Significance of results is listed next to labels (***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$). Sample sizes are listed to the right of each row.

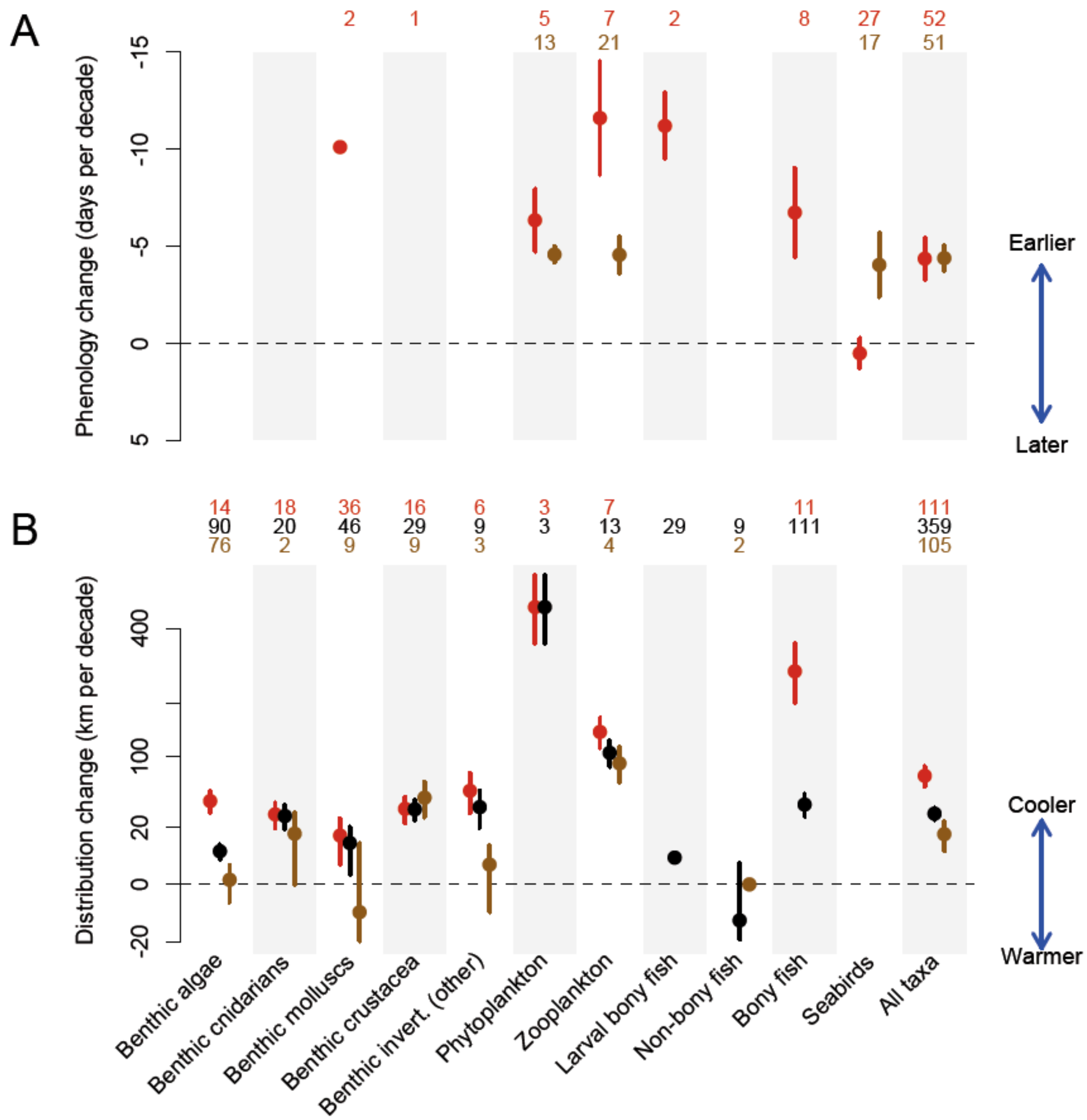


Figure 30-11: Rates of change in (A) phenology (days.decade^{-1}) measured during spring (red) and summer (brown); and (B) distribution (km.decade^{-1}) for marine taxonomic groups, measured at the leading edges (red), and trailing edges (brown). O (brown). Average distribution shifts calculated using all data, regardless of range location, are in black. Distribution rates have been square-root transformed; standard errors may be asymmetric as a result. Positive distribution changes are consistent with warming (into previously cooler waters, generally poleward) and negative phenological changes are consistent with warming (generally earlier). Means ± standard error are shown, with number of observations and significance (*p<0.1, **p<0.05, ***p<0.01); Poloczanska et al, 2013).

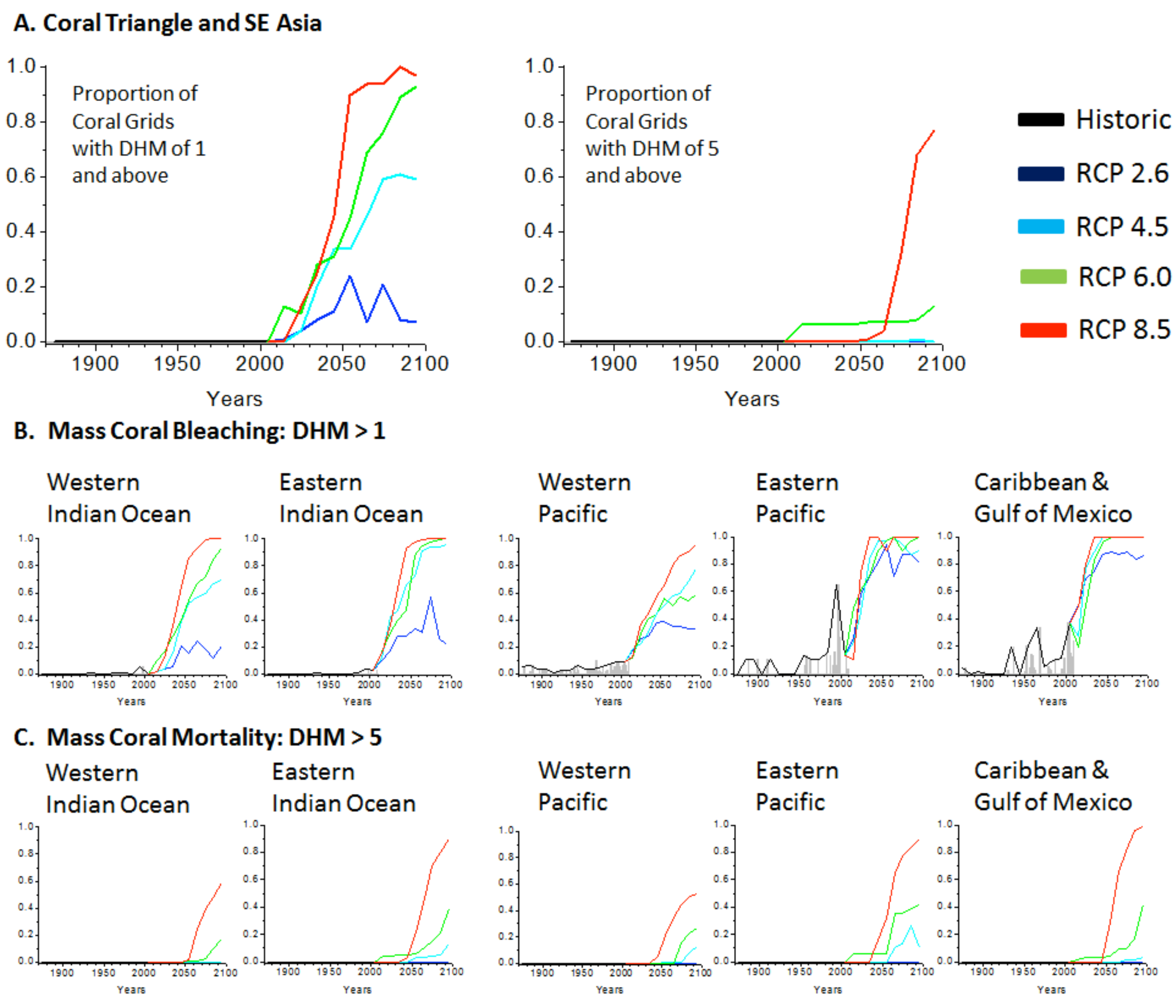


Figure 30-12: Annual maximum proportions of reef pixels with Degree Heating Months (Donner et al. 2007; DHM) ≥ 1 (coral bleaching) and DHM ≥ 5 (bleaching across 100% of affected areas with significant mortality, Eakin et al. 2010) for each of the six coral regions (Figure 30.3) have been depicted as bar graphs for the period 1870-2009. This part of the graph is derived from the HadISST 1.1 data set. The black line plotted on top of the bar graphs is the maximum annual area value for each decade over the period 1870-2009. This value is continued through 2010-2099 using CMIP-5 data and splits into the four Representative Concentration Pathways (RCP 2.6, 4.5, 6.0 and 8.5). DHMs were produced for each of the four RCPs using the ensembles of CMIP models. From these global maps of DHMs the annual percentage of grid cells with DHM ≥ 1 and DHM ≥ 5 were calculated for each coral region. These data were then grouped into decades from which the maximum annual proportions were derived. The plotted lines for 2010-2099 are the average of these maximum proportion values for each RCP. Monthly SST anomalies are derived using a 1985-2000 maximum monthly mean (MMM) climatology derived in the calculations for Figure 30.4. This was done separately for HadISST 1.1 and each of the CMIP-5 models and each of the four RCPs, at each grid cell for each region. DHMs are then derived by adding up the monthly anomalies using a 4 month rolling sum.

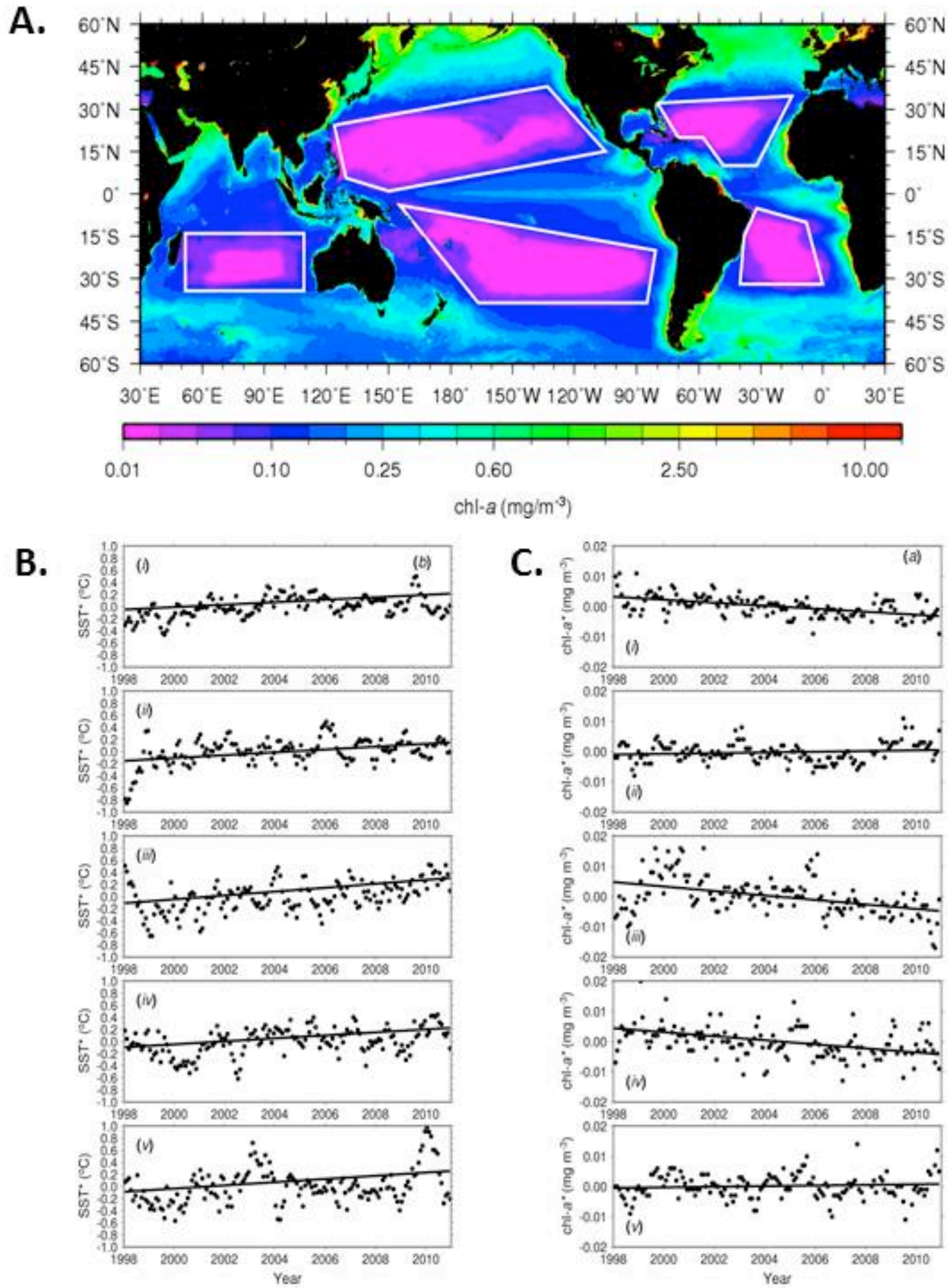


Figure 30-13: A. Map of SeaWiFS chl-a climatology. The white polygons define the sub-regions that were analyzed and represent the major sub-regions considered as sub-tropical gyres by Signorini and McClain (2012). B. Time series of anomalies in chl-a and B. Sea Surface Temperature SST for STGs in North Pacific (NPAC), South Pacific (SPAC), Indian Ocean (IOCE) North Atlantic (NATL) and South Atlantic (SATL) Oceans.

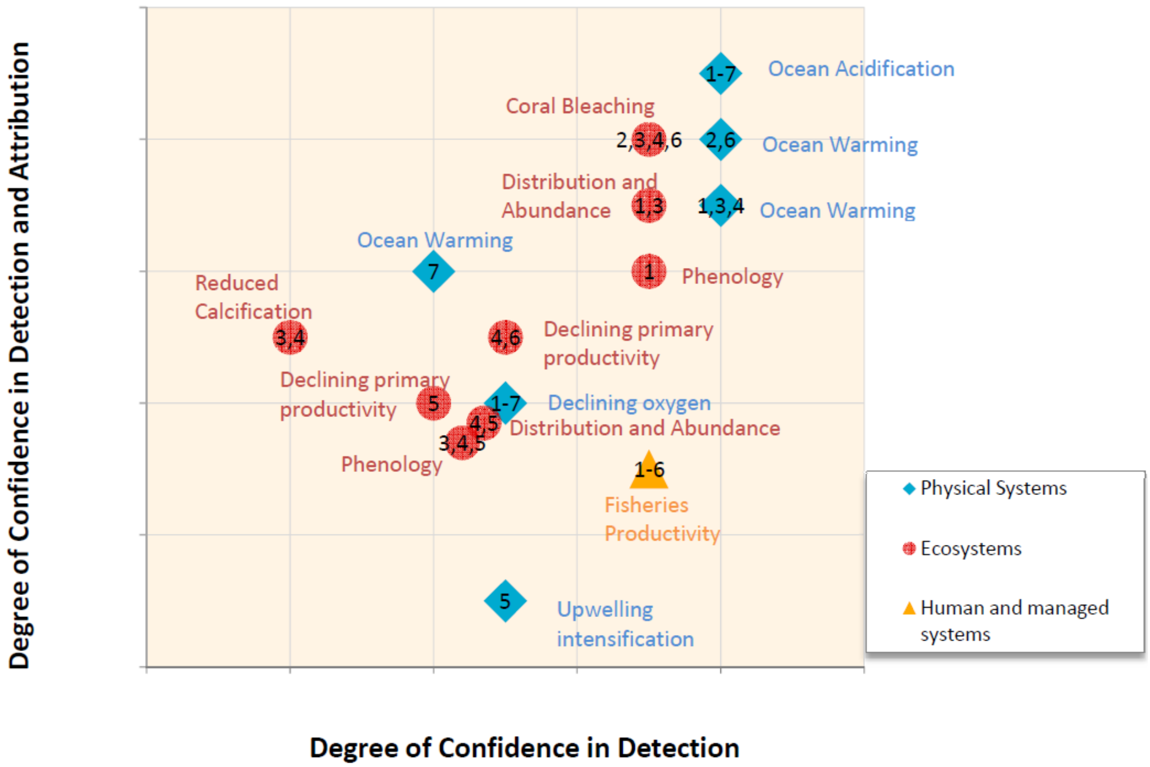
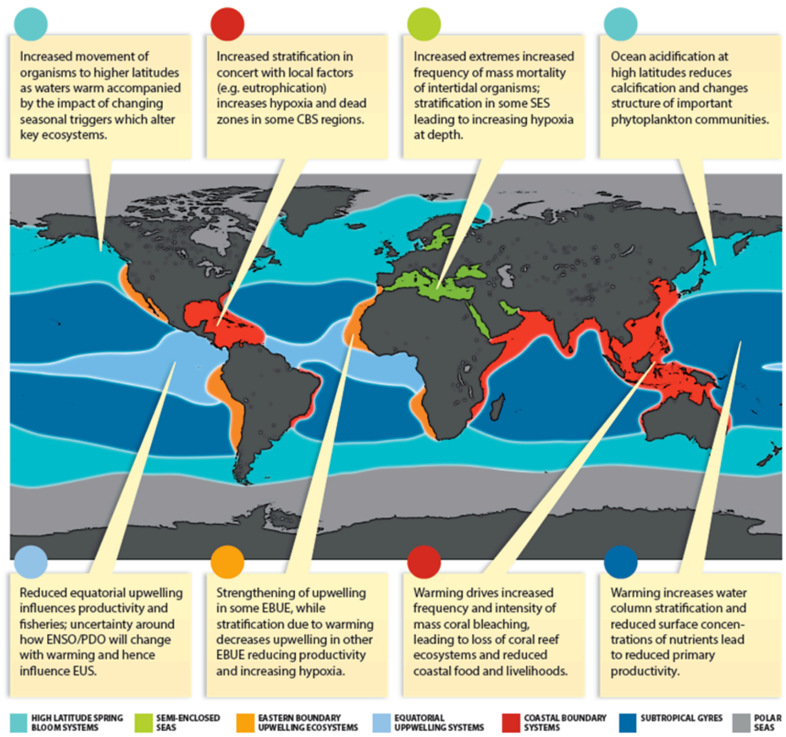


Figure 30-14: Expert assessment of degree of confidence in detection and attribution across sub-regions and processes (based on evidence explored throughout Chapter 30).

A. KEY RISKS and VULNERABILITIES



B. IMPACTS ON FISHERIES

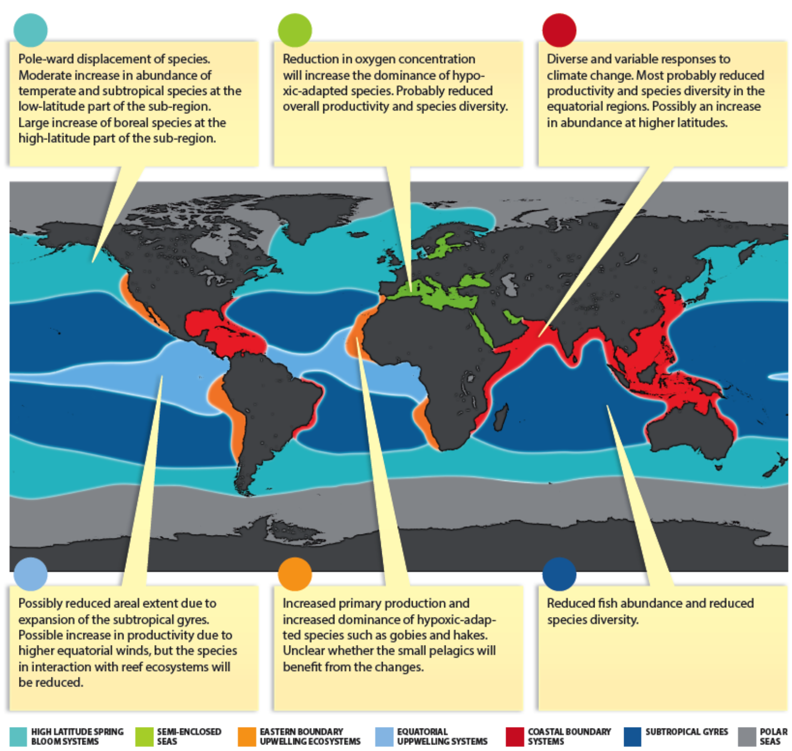
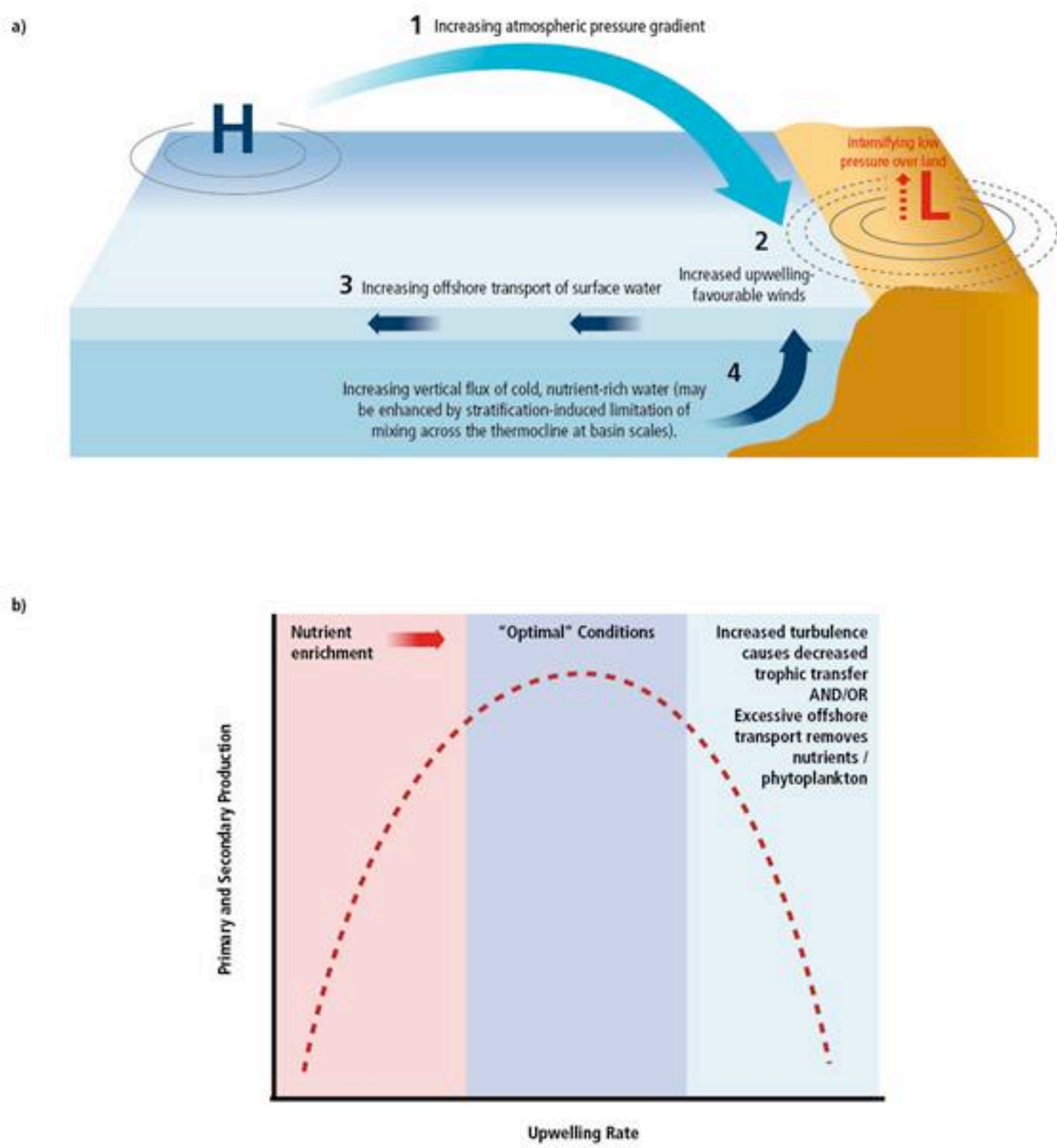


Figure 30-15: A. Summary of regional impacts and opportunities associated with climate change on the world's ocean region. B. Example of changes occurring within fisheries across the Ocean.



Box 30-1 Figure Caption: Diagram illustrating the interaction between land and coastal sea temperature, wind direction and strength, and coastal upwelling.

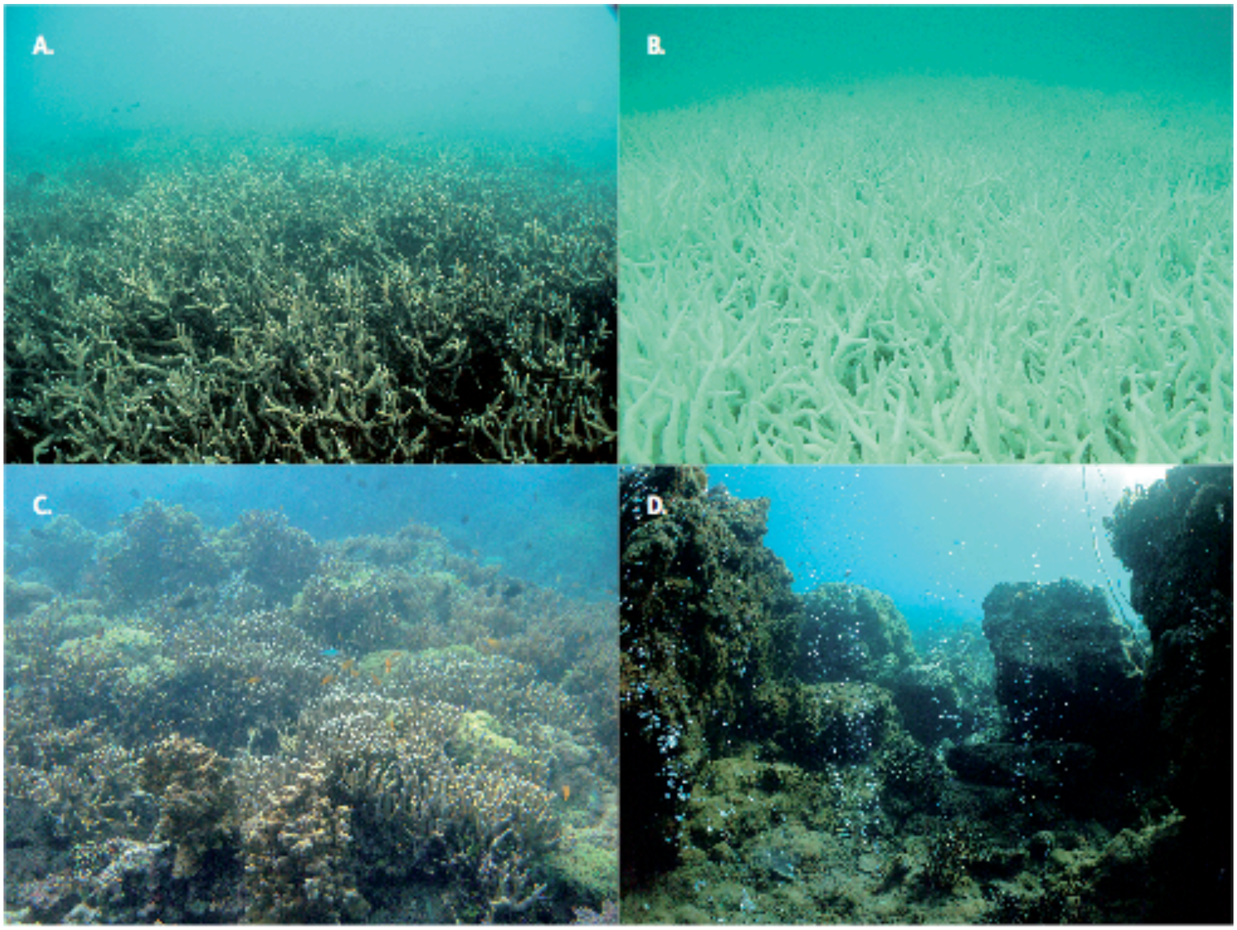


Figure CR-1: A and B: the same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Coral cover at the time of bleaching was 95% bleached almost all of it severely bleached, resulting in mortality of 20.9% (Elvidge et al., 2004). Mortality was comparatively low due in part because these communities were able shuffle symbiont types to more thermo-tolerant types (Berkelmans and van Oppen, 2006; Jones et al., 2008). C and D: three CO2 seeps in Milne Bay Province, Papua New Guinea show that prolonged exposure to high CO2 is related to fundamental changes in coral reef structures (Fabricius et al., 2011). Coral communities at three high CO2 (Fig. XB; median pHT 7.7, 7.7 and 8.0), compared with three control sites (Fig. XA; median pHT 8.02), are characterized by significantly reduced coral diversity (-39%), severely reduced structural complexity (-67%), low densities of young corals (-66%) and few crustose coralline algae (-85%). Reef development ceases at pHT values below 7.7. Photo credit: R. Berkelmans (A and B) and K. Fabricius (C and D).

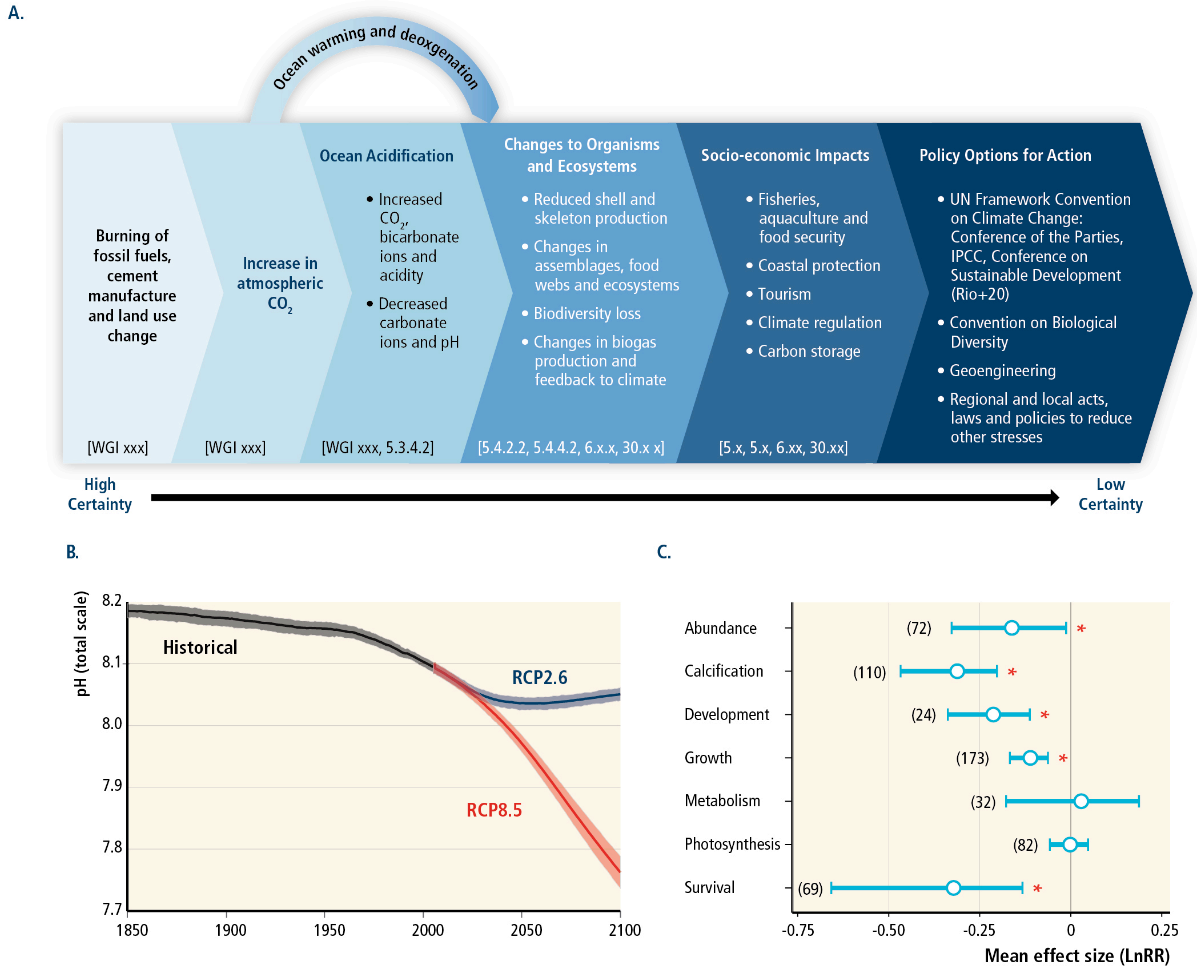


Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley & Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (IPCC AR5 WG1 report, Figure 6.28). C: Effect of near future acidification on major response variables estimated using weighted random effects meta-analyses, with the exception of survival which is not weighted (Kroeker et al., in press). The effect size indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a significant effect.