30

The Ocean

Coordinating Lead Authors:
Ove Hoegh-Guldberg (Australia), Rongshuo Cai (China)

Lead Authors:
Elvira S. Poloczanska (Australia), Peter G. Brewer (USA), Svein Sundby (Norway), Karim Hilmi (Morocco), Victoria J. Fabry (USA), Sukgeun Jung (Republic of Korea)

Contributing Authors:
William Skirving (USA), Dáithí Stone (Canada/South Africa/USA), Michael T. Burrows (UK), Johann Bell (New Caledonia), Long Cao (China), Simon Donner (Canada), C. Mark Eakin (USA), Arne Eide (Norway), Benjamin Halpern (USA), Charles R. McClain (USA), Mary I. O'Connor (Canada), Camille Parmesan (USA), R. Ian Perry (Canada), Anthony J. Richardson (Australia), Christopher J. Brown (Australia), David Schoeman (Australia), Sergio Signorini (USA), William Sydeman (USA), Rui Zhang (China), Ruben van Hooidonk (USA), Stewart M. McKinnell (PICES/Canada)

Review Editors:
Carol Turley (UK), Ly Omar (Senegal)

Volunteer Chapter Scientists:
Jo Davy (New Zealand), Sarah Lee (USA)

This chapter should be cited as:

Hoegh-Guldberg, O., R. Cai, E.S. Poloczanska, P.G. Brewer, S. Sundby, K. Hilmi, V.J. Fabry, and S. Jung, 2014: The Ocean. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1655-1731.

Table of Contents

Frequently Asked Questions

Executive Summary

The Ocean plays a central role in Earth's climate and has absorbed 93% of the extra energy from the enhanced greenhouse effect and approximately 30% of anthropogenic carbon dioxide (CO_2) from the atmosphere. Regional responses are addressed here by dividing the Ocean into seven sub-regions: High-Latitude Spring Bloom Systems (HLSBS), Eastern Boundary Upwelling Ecosystems (EBUE), Coastal Boundary Systems (CBS), Equatorial Upwelling Systems (EUS), Subtropical Gyres (STG), Semi-Enclosed Seas (SES), and the Deep Sea (DS; >1000 m). An eighth region, Polar Seas, is dealt with by Chapter 28. {Figure 30-1; WGI AR5 6.3.1; WGI AR5 Boxes 3.1, 3.8}

30

Global average sea surface temperatures have increased since both the beginning of the 20th century and the 1950s (certain). The average sea surface temperature (SST) of the Indian, Atlantic, and Pacific Oceans has increased by 0.65°C, 0.41°C, and 0.31°C, respectively, over the period 1950–2009 (*very likely*, *p*-value ≤ 0.05). Changes in the surface temperatures of the ocean basins are consistent with temperature trends simulated by ocean-atmosphere models with anthropogenic greenhouse gas (GHG) forcing over the past century (*high confidence*). Sub-regions within the Ocean also show *robust evidence* of change, with the influence of long-term patterns of variability (e.g., Pacific Decadal Oscillation (PDO); Atlantic Multi-decadal Oscillation (AMO)) contributing to variability at regional scales, and making changes due to climate change harder to distinguish and attribute. {30.3.1; Figure 30-2e-g; Table 30-1; WGI AR5 2.4.2-3, 3.2, 10.4.1, 14}

Uptake of CO_2 has decreased ocean pH (approximately 0.1 unit over 100 years), fundamentally changing ocean carbonate chemistry in all ocean sub-regions, particularly at high latitudes (*high confidence*). The current rate of ocean acidification is unprecedented within the last 65 Ma (*high confidence*), if not the last 300 Ma (*medium confidence*). Warming temperatures, and declining pH and carbonate ion concentrations, represent risks to the productivity of fisheries and aquaculture, and the security of regional livelihoods given the direct and indirect effects of these variables on physiological processes (e.g., skeleton formation, gas exchange, reproduction, growth, and neural function) and ecosystem processes (e.g., primary productivity, reef building and erosion) (*high confidence*). {6.1.2, 6.2-3, 30.3.2, 30.6; WGI AR5 3.8.2; WGI AR5 Boxes 3.2, 5.3.1}

Regional changes observed in winds, surface salinity, stratification, ocean currents, nutrient availability, and oxygen depth profile in many regions may be a result of anthropogenic GHG emissions (*low* to *medium confidence*). Marine organisms and ecosystems are *likely* to change in response to these regional changes, although evidence is limited and responses uncertain. {6.2-3, 30.3, 30.5; WGI AR5 2.7, 3.3-8, 10.4.2, 10.4.4}

Most, if not all, of the Ocean will continue to warm and acidify, although the rates will vary regionally (*high confidence*). Differences between Representative Concentration Pathways (RCPs) are *very likely* to be minimal until 2040 (*high confidence*). Projected temperatures of the surface layers of the Ocean, however, diverge as the 21st century unfolds and will be 1°C to 3°C higher by 2100 under RCP8.5 than RCP2.6 across most ocean sub-regions. The projected changes in ocean temperature pose serious risks and vulnerabilities to ocean ecosystems and dependent human communities (*robust evidence*, *high agreement*; *high confidence*). {6.5, 30.3.1-2, 30.7.1; Figure 30-2e-g; Table 30-3; WGI AR5 11.3.3, 12.4.7; WGI AR5 Box 1.1}

Rapid changes in physical and chemical conditions within ocean sub-regions have already affected the distribution and abundance of marine organisms and ecosystems. Responses of species and ecosystems to climate change have been observed from every ocean sub-region (*high confidence*). Marine organisms are moving to higher latitudes, consistent with warming trends (*high confidence*), with fish and zooplankton migrating at the fastest rates, particularly in HLSBS regions. Changes to sea temperature have also altered the phenology, or timing of key life-history events such as plankton blooms, and migratory patterns and spawning in fish and invertebrates, over recent decades (*medium confidence*). There is *medium* to *high agreement* that these changes pose significant uncertainties and risks to fisheries, aquaculture, and other coastal activities. Ocean acidification maybe driving similar changes (*low confidence*), although there is *limited evidence* and *low agreement* at present. The associated risks will intensify as ocean warming and acidification continue. {6.3-4, 30.4-5; Table 30-3; Box CC-MB}

Regional risks and vulnerabilities to ocean warming and acidification can be compounded by non-climate related stressors such as pollution, nutrient runoff from land, and over-exploitation of marine resources, as well as natural climate variability (*high confidence*). These influences confound the detection and attribution of the impacts of climate change and ocean acidification on ecosystems yet may also represent opportunities for reducing risks through management strategies aimed at reducing their influence, especially in CBS, SES, and HLSBS. {5.3.4, 18.3.3-4, 30.1.2, 30.5-6}

Recent changes to wind and ocean mixing within the highly productive HLSBS, EBUE, and EUS are *likely* to influence energy transfer to higher trophic levels and microbial processes. There is, however, *limited evidence* and *low agreement* on the direction and magnitude of these changes and their relationship to ocean warming and acidification (*low confidence*). In cases where Net Primary Productivity (NPP) increases or is not consumed (e.g., Benguela EBUE, *low confidence*), the increased transfer of organic carbon to deep regions can stimulate microbial respiration and reduce O_2 levels (*medium confidence*). Oxygen concentrations are also declining in the tropical Pacific, Atlantic, and Indian Oceans (particularly EUS) due to reduced O_2 solubility at higher temperatures, and changes in ocean ventilation and circulation. {6.3.3, 30.3, 30.5.1-2, 30.5.5; Box CC-PP; WGI AR5 3.8.3}

Global warming will result in more frequent extreme events and greater associated risks to ocean ecosystems (*high confidence*). In some cases (e.g., mass coral bleaching and mortality), projected increases will eliminate ecosystems, and increase risks and vulnerabilities to coastal livelihoods and food security (e.g., CBS in Southeast Asia; SES, CBS, and STG in the Indo-Pacific) (*medium* to *high confidence*). Reducing stressors not related to climate change represents an opportunity to strengthen the ecological resilience within these regions, which may help them survive some projected changes in ocean temperature and chemistry. {5.4, 30.5.3-4, 30.5.6, 30.6.1; Figure 30-4; Box CC-CR; IPCC, 2012}

The highly productive HLSBS in the Northeastern Atlantic has changed in response to warming (*medium evidence*, *high agreement*), with a range of consequences for fisheries. These ecosystems are responding to recent warming, with the greatest changes being observed since the late 1970s in the phenology, distribution, and abundance of plankton assemblages, and the reorganization of fish assemblages (*high confidence*). There is *medium confidence* that these changes will have both positive and negative implications depending on the particular HLSBS fishery and the time frame. {6.4.1.1, 6.5.3, 30.5.1, 30.6.2.1; Boxes CC-MB, 6-1}

EUS, which support highly productive fisheries off equatorial Africa and South America, have warmed over the past 60 years (Pacific EUS: 0.43°C, Atlantic EUS: 0.54°C; *very likely*, *p*-value ≤ 0.05). Although warming is consistent with changes in upwelling intensity, there is *low confidence* in our understanding of how EUS will change, especially in how El Niño-Southern Oscillation (ENSO) and other patterns of variability will interact in a warmer world. The risk, however, of changes to upwelling increases with average global temperature, posing significant uncertainties for dependent ecosystems, communities, and fisheries. {30.5.2; WGI AR5 14.4}

The surface waters of the SES show significant warming from 1982 and most CBS show significant warming since 1950. Warming of the Mediterranean has led to the recent spread of tropical species invading from the Atlantic and Indian Oceans. Projected warming increases the risk of greater thermal stratification in some regions, which can lead to reduced O_2 ventilation and the formation of additional hypoxic zones, especially in the Baltic and Black Seas (*medium confidence*). In some CBS, such as the East China Sea and Gulf of Mexico, these changes are further influenced by the contribution of nutrients from coastal pollution contributing to the expansion of hypoxic (low O_2) zones. These changes are *likely* to influence regional ecosystems as well as dependent industries such as fisheries and tourism, although there is *low confidence* in the understanding of potential changes and impacts. {5.3.4.3, 30.5.3-4; Table 30-1}

Coral reefs within CBS, SES, and STG are rapidly declining as a result of local stressors (i.e., coastal pollution, overexploitation) and climate change (*high confidence*). Elevated sea temperatures drive impacts such as mass coral bleaching and mortality (*very high confidence*), with an analysis of the Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble projecting the loss of coral reefs from most sites globally by 2050 under mid to high rates of ocean warming (*very likely*). {29.3.1.2, 30.5.3-4, 30.5.6; Figure 30-10; Box CC-CR}

The productive EBUE and EUS involve upwelling waters that are naturally high in CO_2 concentrations and low in pH, and hence are potentially vulnerable to ocean warming and acidification (*medium confidence*). There is *limited evidence* and *low agreement* as to how upwelling systems are *likely* to change (*low confidence*). Declining O_2 and shoaling of the aragonite saturation horizon through ocean acidification increase the risk of upwelling water being low in pH and O_2, with impacts on coastal ecosystems and fisheries, as has been seen already (e.g., California Current EBUE). These risks and uncertainties are *likely* to involve significant challenges for fisheries and associated livelihoods along the west coasts of South America, Africa, and North America (*low* to *medium confidence*). {22.3.2.3, 30.3.2.2, 30.5.2, 30.5.5; Boxes CC-UP, CC-PP}

Chlorophyll concentrations measured by satellites have decreased in the STG of the North Pacific, Indian, and North Atlantic Oceans by 9%, 12%, and 11%, respectively, over and above the inherent seasonal and interannual variability from 1998 to 2010 (*high confidence*; *p*-value ≤ 0.05). Significant warming over this period has resulted in increased water column stratification, reduced mixed layer depth, and possibly decreases in nutrient availability and ecosystem productivity (*limited evidence*, *medium agreement*). The short time frame of these studies against well-established patterns of long-term variability leads to the conclusion that these changes are *about as likely as not* due to climate change. {6.3.4, 30.5.6; Table 30-1; Box CC-PP; WGI AR5 3.8.4}

30

The world's most abundant yet difficult to access habitat, the DS, is changing (*limited evidence*, *medium agreement*), with warming between 700 and 2000 m from 1957 to 2010 *likely* to involve a significant anthropogenic signal (*medium confidence*). Decreased primary productivity of surface waters (e.g., STG) is *likely* to reduce the availability of organic carbon to DS ecosystems. Understanding of the risks of climate change and ocean acidification to the DS is important given the size of the DS region but is limited (*low confidence*). {30.5.7; Figure 30-2; WGI AR5 3.2.4; WGI AR5 Figures 3.2, 3.9}

Changes to surface wind and waves, sea level, and storm intensity will increase the vulnerability of ocean-based industries such as shipping, energy, and mineral extraction (*medium confidence*). Risks to equipment and people may be reduced through the design and use of ocean-based infrastructure, together with the evolution of policy (*medium agreement*). Risks and uncertainties will increase with further climate change. New opportunities as well as risks for shipping, energy, and mineral extraction, and international issues over access and vulnerability, may accompany warming waters, particularly at high latitudes. {10.2.2, 10.4.4, 28.2.6, 28.3.4, 30.3.1, 30.6.2; IPCC, 2012}

Changes to ocean temperature, chemistry, and other factors are generating new challenges for fisheries, as well as benefits (*high agreement*). Climate change is a risk to the sustainability of capture fisheries and aquaculture development, adding to the threats of over-fishing and other non-climate stressors. In EUS and STG, shifts in the distribution and abundance of large pelagic fish stocks will have the potential to create "winners" and "losers" among island nations and economies. There has been a boost in fish stocks of high-latitude fisheries in the HLSBS of the North Pacific and North Atlantic, partly as a result of 30 years of increase in temperature. This is *very likely* to continue, although some fish stocks will eventually decline. A number of practical adaptation options and supporting international policies can minimize the risks and maximize the opportunities. {7.4.2, 7.5.1.1.2, 29.4, 30.6-7}

Adaptation strategies for ocean regions beyond coastal waters are generally poorly developed but will benefit from international legislation and expert networks, as well as marine spatial planning (*high agreement*). Fisheries and aquaculture industries with high technology and/or large investments, as well as marine shipping and oil and gas industries, have high capacities for adaptation due to greater development of environmental monitoring, modeling, and resource assessments. For smaller scale fisheries and developing nations, building social resilience, alternative livelihoods, and occupational flexibility represent important strategies for reducing the vulnerability of ocean-dependent human communities. Building strategies that include climate forecasting and early-warning systems can reduce impacts of warming and ocean acidification in the short term. Overall, there is a strong need to develop ecosystem-based monitoring and adaptation strategies to mitigate rapidly growing risks and uncertainties to the coastal and oceanic industries, communities, and nations (*high agreement*). {7.5.1.1, 30.6}

Significant opportunity exists within the Ocean and its sub-regions for reducing the CO_2 flux to the atmosphere (*limited evidence*, *medium agreement*). Ecosystems such as mangroves, seagrass, and salt marsh offer important carbon storage and sequestration opportunities (e.g., Blue Carbon; *limited evidence*, *medium agreement*). Blue Carbon strategies can also be justified in terms of the ecosystem services provided by coastal vegetated habitats such as protection against coastal erosion and storm damage, and maintenance of habitats for fisheries species. Sequestration of anthropogenic CO_2 into deep ocean areas still faces considerable hurdles with respect to the expense, legality, and vulnerability of storage sites and infrastructure. There are also significant opportunities with the Ocean for the development of offshore renewable energy such as wind and tidal power. {5.5.7, 30.6.1, 30.6.4}

International frameworks for collaboration and decision making are critically important for coordinating policy that will enable mitigation and adaptation by the Ocean sectors to global climate change (e.g., United Nations Convention on the Law of the Sea (UNCLOS)). These international frameworks offer an opportunity to solve problems collectively, including improving fisheries management across national borders (e.g., reducing illegal, unreported, and unregulated (IUU) fishing), responding to extreme events, and strengthening international food security. Given the importance of the Ocean to all countries, there is a need for the international community to progress rapidly to a "whole of ocean" strategy for responding to the risks and challenges posed by anthropogenic ocean warming and acidification. {30.7.2}

30.1. Introduction

The Ocean exerts a profound influence as part of the Earth, interacting with its atmosphere, cryosphere, land, and biosphere to produce planetary conditions. It also directly influences human welfare through the provision and transport of food and resources, as well as by providing cultural and economic benefits. The Ocean also contributes to human welfare indirectly through the regulation of atmospheric gas content and the distribution of heat and water across the planet. This chapter examines the extent to which regional changes to the Ocean can be accurately detected and attributed to anthropogenic climate change and ocean acidification, building on the conclusions of Chapter 6, which focuses on the marine physiological and ecological responses to climate change and ocean acidification. Detailed assessment of the role of recent physical and chemical changes within the Ocean to anthropogenic climate change is provided in WGI AR5 (particularly Chapters 2, 3, 13, and 14). In this chapter, impacts, risks, and vulnerabilities associated with climate change and ocean acidification are assessed for seven ocean sub-regions, and the expected consequences and adaptation options for key ocean-based sectors are discussed. Polar oceans (defined by the presence of sea ice in the north and by the Polar Front in the south) are considered in Chapter 28.

Given that climate change affects coastal and low-lying sub-regions of multiple nations, detailed discussion of potential risks and consequences for these regions occurs in the relevant chapters of this report (e.g., Chapters 5 and 29, as well as other regional sections).

30.1.1. Major Sub-regions within the Ocean

The Ocean represents a vast region that stretches from the high tide mark to the deepest oceanic trench (11,030 m) and occupies 71% of the Earth's surface. The total volume of the Ocean is approximately 1.3 billion km^3, with approximately 72% of this volume being below 1000 m (Deep Sea (DS); Section 30.5.7). There are considerable challenges in assessing the regional impacts of climate change on the Ocean. Devising an appropriate structure to explore the influence of climate change across the entire Ocean region and the broad diversity of life forms and habitats is challenging. Longhurst (1998) identified more than 50 distinct ecological provinces in the Ocean, defined by physical characteristics 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 within AR5. Consequently, comparable principles were used with a division of the non-polar ocean into seven larger sub-regions similar to Barber (1988). It is recognized that these sub-regions do not always match physical-chemical patterns or specific geographies, and that they interact strongly with terrestrial regions through weather systems and the exchange of materials. Different ocean sub-regions may also have substantially different primary productivities and fishery catch. Notably, more than 80% of fishery catch is associated with three ocean sub-regions: Northern Hemisphere High-Latitude Spring Bloom Systems (HLSBS), Coastal Boundary Systems (CBS), and Eastern Boundary Upwelling Ecosystems (EBUE; Table SM30-1, Figure 30-1). The DS (>1000 m) is included as a separate category that overlaps with the six other ocean sub-regions dealt with in this chapter.

30.1.2. Detection and Attribution of Climate Change and Ocean Acidification in Ocean Sub-regions

The central goal of this chapter is to assess the recent literature on the Ocean as a region for changes that can be attributed to climate change and/or ocean acidification. Detailed assessments of recent physical and chemical changes in the Ocean are outlined in WGI AR5 Chapters 2, 3, 6, 10, 13, and 14. The detection and attribution of climate change and ocean acidification on marine organisms and ecosystems is addressed in Chapter 6. This chapter draws on these chapters to investigate regional changes in the physical, chemical, ecological, and socioeconomic aspects of the Ocean and the extent to which they can be attributed to climate change and ocean acidification.

Generally, successful 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 probable explanation for the detected change in question (Section 18.2.1.1). Comparing detected changes with the expectations of well-established scientific evidence also plays a central role in the successful attribution of detected changes. This was attempted for seven sub-regions of the Ocean. There are a number of general limitations to the detection and attribution of impacts to climate change and ocean acidification that are discussed elsewhere (Section 18.2.1) along with challenges (Section 18.2.2). Different approaches and "best practice" guidelines are discussed in WGI AR5 Chapters 10 and 18, as well as in several other places (Hegerl et al., 2007, 2010; Stott et al., 2010). The fragmentary nature of ocean observing, structural uncertainty in model simulations, the influence of long-term variability, and confounding factors unrelated to climate change (e.g., pollution, introduced species, over-exploitation of fisheries) represent major challenges (Halpern et al., 2008; Hoegh-Guldberg et al., 2011b; Parmesan et al., 2011). Different factors may also interact synergistically or antagonistically with each other and climate change, further challenging the process of detection and attribution (Hegerl et al., 2007, 2010).

30.2. Major Conclusions from Previous Assessments

An integrated assessment of the impacts of climate change and ocean acidification on the Ocean as a region was not included in recent IPCC assessments, 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). The fact that assessments for ocean and coastal systems are spread throughout previous IPCC assessment reports reduces the opportunity for synthesizing the detection and attribution of climate change and ocean acidification across the physical, chemical, ecological, and socioeconomic components of 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 3000 m and that the ocean has been taking up over 80% of the heat being added to the climate system" (AR4 Synthesis Report, p. 30). AR4 also concluded that sea levels had risen due to the thermal expansion of the Ocean but recognized that

(a)

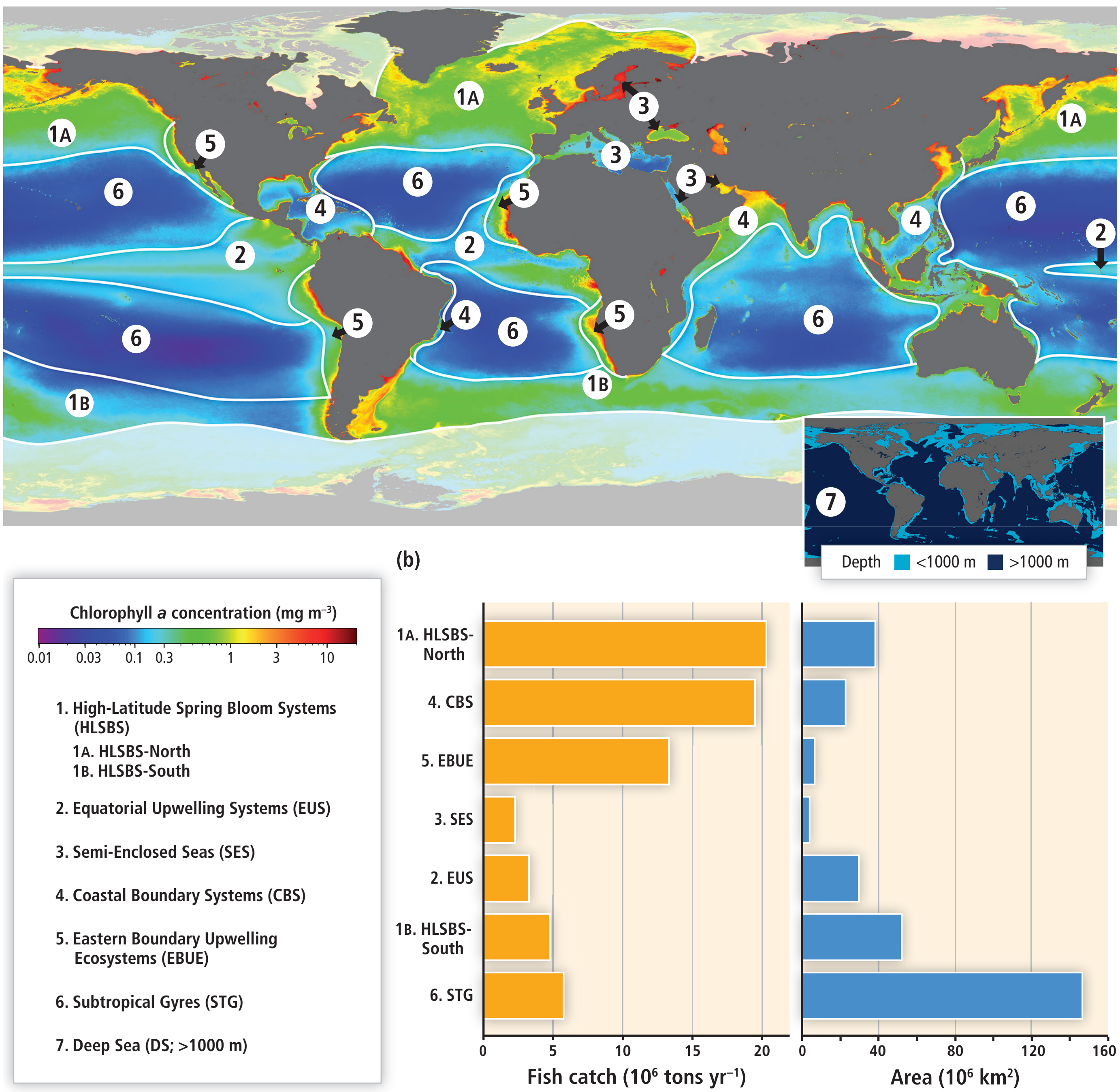


Figure 30-1 | (a) Separation of the world's oceans into seven major sub-regions (excluding an eighth area, Polar Oceans, which is considered in Chapter 28; white shaded area). The chlorophyll-*a* signal measured by SeaWiFS and averaged over the period from Sep 4, 1997 to 30 Nov 2010 (NASA) provides a proxy for differences in marine productivity (with the caveats provided in Box CC-PP). Ecosystem structure and functioning, as well as key oceanographic features, provided the basis for separating the Ocean into the sub-regions shown. The map insert shows the distribution of Deep Sea (DS) habitat (>1000 m; Bathypelagic and Abyssopelagic habitats combined). (b) Relationship between fish catch and area for each ocean subregion. Left panel: average fish catch (as millions tons yr^{-1}) for the period 1970–2006. Right panel: surface area (millions km^2). The top three bars (subregions HLSBS-North, CBS, and EBUE) cover 19% of the world oceans' area and provide 76% of the world's fish catches. Values for fish catch, area, and primary productivity of the ocean sub-regions are listed in Table SM30-1.

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 boundary for sea level rise" (WGI AR4 SPM). Changes to ocean temperature and density have been identified as having the potential to alter large-scale ocean circulation. AR4 concluded that, with respect to the Meridional Overturning Circulation (MOC), "it is *very likely* that up to the end of the 20th century the MOC was changing significantly at interannual to decadal time scales" (WGI AR4 Box 5.1, p. 397), despite limited evidence of a slowing MOC.

According to AR4, "Sea-level rise over the last 100 to150 years is probably contributing to coastal erosion in many places," including the east coast of the United States and the United Kingdom (WGII AR4 Section 1.3.3.1, p. 92). The AR4 assessment was *virtually certain* that rising atmospheric carbon dioxide (CO_2) had changed carbonate chemistry of the ocean (i.e., buffering capacity, carbonate and bicarbonate concentrations), and that a decrease in surface pH of 0.1 had occurred over the global ocean (calculated from the uptake of anthropogenic CO_2 between 1750 and 1994; Sabine et al., 2004; Raven et al., 2005; WGI AR4 Section 5.4.2.3; WGI AR4 Table 7.3). Large-scale changes in ocean salinity were also observed from 1955 to 1998 and were "characterized by a global freshening in sub-polar latitudes and salinification of shallower parts of the tropical and subtropical oceans" (WGI AR4 Chapter 5 ES, p. 387). In this case, freshening was observed in the Pacific, with increased salinity being observed in the Atlantic and Indian Oceans (WGI AR4 Sections 5.3.2-5). These changes in surface salinity were qualitatively consistent with 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" (WGI AR4 SPM, p. 7).

Substantial evidence presented in AR4 indicated that changing ocean conditions have extensively influenced marine ecosystems (WGII AR4 Table 1.5). 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 (SST) and to a lesser extent by modification of precipitation regimes and wind patterns" (WGII AR4 Section 1.3.4.2, p. 94). Observed changes in marine ecosystems and managed fisheries reported within AR4 included changes to plankton community structure and productivity, the phenology and biogeography of coastal species, intertidal communities on rocky shores, kelp forests, and the distribution of pathogens and invasive species. Changes were also observed in coral reefs (primarily increased mass coral bleaching and mortality) and migratory patterns and trophic interactions of marine birds, reptiles, and mammals, as well as of a range of other marine organisms and ecosystems (WGII AR4 Table 1.5), although a separate exercise in detection and attribution of changes due to climate change (as done for terrestrial studies) was not done as part of AR4.

30.3. Recent Changes and Projections of Future Ocean Conditions

Evidence that increasing concentrations of atmospheric CO_2 have resulted in the warming and acidification of the upper layers of the Ocean has strengthened since AR4. Understanding the full suite of physical and chemical changes to the Ocean is critical to the interpretation of the past and future responses of marine organisms and ecosystems, especially with respect to the implications for coastal and low-lying areas.

30.3.1. Physical Changes

30.3.1.1. Heat Content and Temperature

The Ocean has absorbed 93% of the extra heat arising from the enhanced greenhouse effect (1971–2010), with most of the warming (64%) occurring in the upper (0 to 700 m) ocean (1971–2010; WGI AR5 Section 3.2.3, Figure 3.2, Box 3.1). It is certain that global average SSTs have increased since the beginning of the 20th century, with improvements and growth of data sets and archives, and the understanding of errors and biases since AR4 (WGI AR5 Section 2.4.2). It is *virtually certain* that the upper ocean (0 to 700 m depth) has warmed from 1971 to 2010 (Figure 30-2a), while it is *likely* that the surface layers of the Ocean have warmed from the 1870s to 1971. Rates of increase in temperature are highest near the surface of the Ocean (>0.1°C per decade in the upper 75 m from 1971 to 2010) decreasing with depth (0.015°C per decade at 700 m; Figure 30-2b,c). It is *very likely* that the intensification of this warming near the surface has increased thermal stratification of the upper ocean by about 4% between 0 and 200 m depth from 1971 to 2010 in all parts of the ocean north of 40°S. It is *likely* that the Ocean has warmed between 700 and 2000 m from 1957 to 2010, with the warming signal becoming less apparent or non-existent at deeper depths (WGI AR5 Sections 3.2.1-3, Figures 3.1, 3.2, 3.9). These changes include a significant anthropogenic signal (*virtually certain*; Gleckler et al., 2012; Pierce et al., 2012), with the surface waters of all three ocean basins warming at different rates that exceed those expected if there were no changes to greenhouse gas (GHG) forcing over the past century (Figure 30-2e,f,g). In this respect, the observed record also falls within the range of historical model outputs that include increases in the concentration of GHGs as opposed to models that do not (Figure 30-2e,f,g).

Data archives such as Hadley Centre Interpolated SST 1.1 (HadISST1.1) contain SSTs reconstructed from a range of sources, allowing an opportunity to explore mean monthly, gridded, global SST from 1870 to the present (Rayner et al., 2003). The published HadISST1.1 data set (higher temporal and spatial resolution than HadSST3) was used to explore trends in historic SST within the sub-regions of the Ocean (Figure 30-1a; see definition of regions in Figure SM30-1 and Table SM30-2, column 1). The median SST for 1871–1995 from the Comprehensive Ocean-Atmosphere Data Set (COADS) were merged with data from the UK Met Office Marine Data Bank (MDB) to produce monthly globally complete fields of SST on a 1° latitude-longitude SST grid from 1870 to the present.

The surface layers of the three ocean basins have warmed (p-value ≤ 0.05, *very likely*), with the Indian Ocean (0.11°C per decade) warming faster than the Atlantic (0.07°C per decade) and Pacific (0.05°C per decade) Oceans (*high confidence*; Table 30-1). This is consistent with the depth-averaged (0 to 700 m) temperature trend observed from 1971 to 2010 (Figure 30-2a).

While some regions (e.g., North Pacific) did not show a clear warming trend, most regions showed either significant warming in the average temperature, or significant warming in either/or the warmest and coolest months of the year, over the period 1950–2009 (HadISST1.1 data; Table 30-1). Trends in SST show considerable sub-regional variability (Table 30-1; Figure 30-2a). Notably, the average temperature of most HLSBS did not increase significantly from 1950 to 2009 (except in the Indian Ocean; Table 30-1) yet the temperatures of the warmest month (North and South Atlantic, and Southeastern Pacific) and of the coolest month (North and South Atlantic, and South Pacific) showed significant upward trends over this period (p-value ≤ 0.05; Table 30-1).

The two EUS warmed from 1950 to 2009 (Pacific EUS: 0.07°C per decade, Atlantic EUS: 0.09°C per decade; Table 30-1). The average monthly SST of the SES did not warm significantly, although the temperature of the coolest month increased significantly within the Baltic Sea (0.35°C per decade or 2.11°C from 1950 to 2009), as did the temperatures of the warmest months in the Black (0.14°C per decade or 0.83°C from 1950 to 2009), Mediterranean (0.11°C per decade or 0.66°C from 1950 to 2009), and Red (0.05°C per decade or 0.28°C from 1950 to 2009) Seas over the period 1950–2009 (*very likely*; Table 30-1). Studies over shorter periods (e.g., 1982–2006; Belkin, 2009) report significant increases in average SST of the Baltic (1.35°C), Black (0.96°C), Red (0.74°C), and Mediterranean (0.71°C) Seas. Such studies

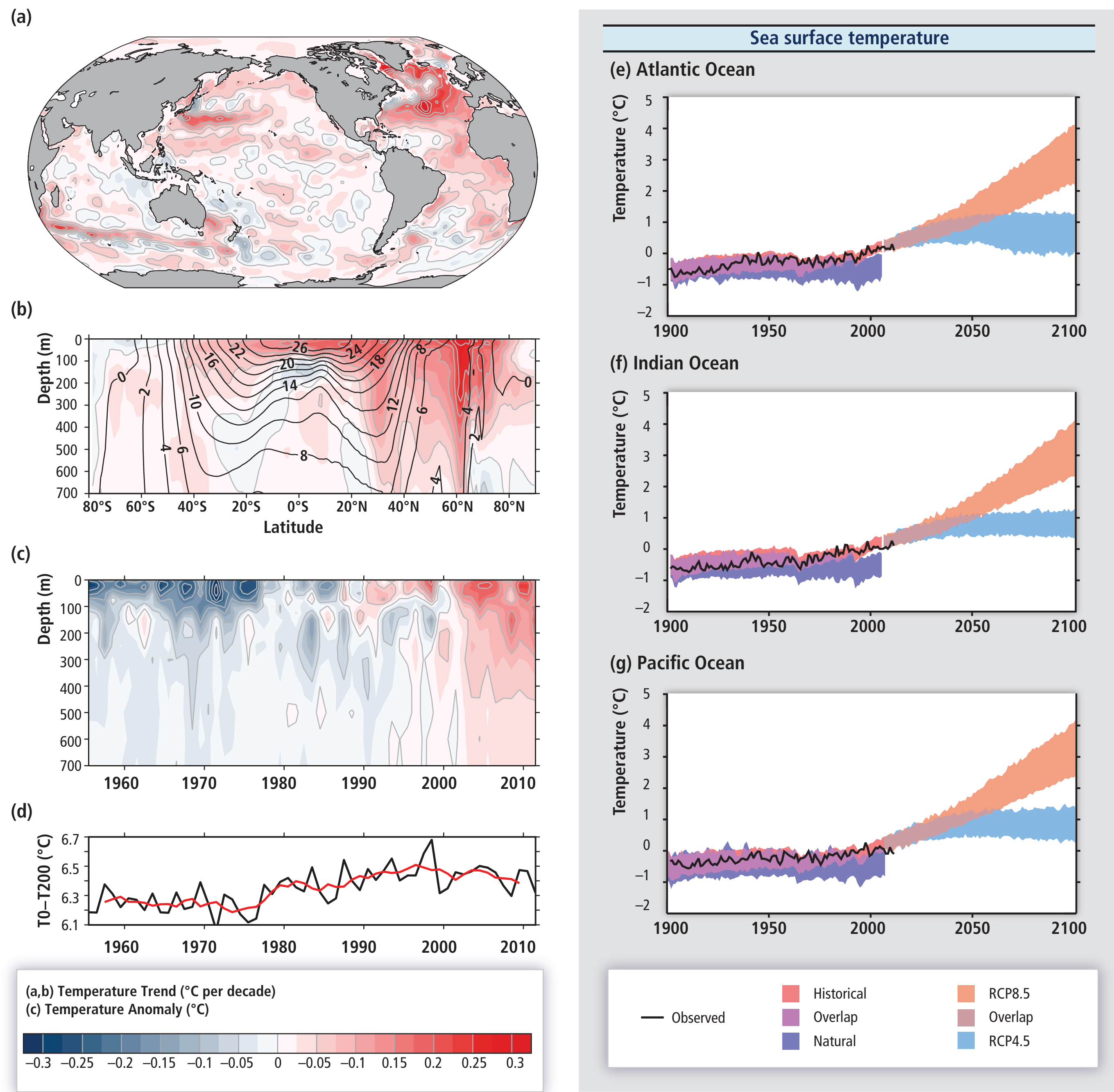


Figure 30-2 | (a) Depth-averaged 0 to 700 m temperature trend for 1971–2010 (longitude vs. latitude, colors and gray contours in degrees Celsius per decade). (b) Zonally averaged temperature trends (latitude vs. depth, colors and gray contours in degrees Celsius per decade) for 1971–2010, with zonally averaged mean temperature over plotted (black contours in degrees Celsius). (c) Globally averaged temperature anomaly (time vs. depth, colors and gray contours in degrees Celsius) relative to the 1971–2010 mean. (d) Globally averaged temperature difference between the Ocean surface and 200 m depth (black: annual values; red: 5-year running mean). [(a–d) from WGI AR5 Figure 3.1] (e)–(g) Observed and simulated variations in past and projected future annual average sea surface temperature over three ocean basins (excluding regions within 300 km of the coast). The black line shows estimates from Hadley Centre Interpolated sea surface temperature 1.1 (HadISST1.1) observational measurements. Shading denotes the 5th to 95th percentile range of climate model simulations driven with "historical" changes in anthropogenic and natural drivers (62 simulations), historical changes in "natural" drivers only (25), and the Representative Concentration Pathways (RCPs; blue: RCP4.5; orange: RCP8.5). Data are anomalies from the 1986–2006 average of the HadISST1.1 data (for the HadISST1.1 time series) or of the corresponding historical all-forcing simulations. Further details are given in Panels (a)-(d) originally presented in WGI AR5 Fig 3.1 and Box 21-2.

Table 30-1 | Regional changes in sea surface temperature (SST) over the period 1950–2009 using the ocean regionalization specified in Figure 30-1(a) (for further details on regions defined for analysis, see Figure SM30-1 and Table SM30-2, column 1). A linear regression was fitted to the average of all 1×1 degree monthly SST data extracted from the Hadley Centre HadISST1.1 data set (Rayner et al., 2003) for each sub-region over the period 1950–2009. All SST values less than −1.8°C, together with all SST pixels that were flagged as being sea ice, were reset to the freezing point of seawater (−1.8°C) to reflect the sea temperature under the ice. Separate analyses were also done to explore trends in the temperatures extracted from the coldest-ranked and the warmest-ranked month of each year (Table SM30-2). The table includes the slope of the regression (°C per decade), the *p*-value for the slope being different from zero and the total change over 60 years (i.e., the slope of linear regression multiplied by six decades) for each category. The *p*-values that exceed 0.05 plus the associated slope and change values have an orange background, denoting the lower statistical confidence in the slope being different from zero (no slope). Note that changes with higher *p*-values may still describe informative trends although the level of confidence that the slope is different from zero is lower.

Sub-region	Area	Regression slope			Total change over 60 years			*p*-value, slope different from zero		
		°C per decade (coolest month)	°C per decade (all months)	°C per decade (warmest month)	Change over 60 years (coolest month)	Change over 60 years (all months)	Change over 60 years (warmest month)	°C per decade (coolest month)	°C per decade (all months)	°C per decade (warmest month)
1. High-Latitude Spring Bloom Systems (HLSBS)	Indian Ocean	0.056	0.087	0.145	0.336	0.522	0.870	0.000	0.003	0.000
	North Atlantic Ocean	0.054	0.073	0.116	0.324	0.438	0.696	0.001	0.15	0.000
	South Atlantic Ocean	0.087	0.063	0.097	0.522	0.378	0.582	0.000	0.098	0.000
	North Pacific Ocean (west)	0.052	0.071	0.013	0.312	0.426	0.078	0.52	0.403	0.462
	North Pacific Ocean (east)	0.016	0.04	0.016	0.096	0.24	0.096	0.643	0.53	0.444
	North Pacific Ocean	0.033	0.055	0.015	0.198	0.33	0.09	0.284	0.456	0.319
	South Pacific Ocean (west)	0.043	0.017	0.044	0.258	0.102	0.264	0.016	0.652	0.147
	South Pacific Ocean (east)	0.047	0.031	0.052	0.282	0.186	0.312	0.000	0.396	0.003
	South Pacific Ocean	0.046	0.027	0.050	0.276	0.162	0.300	0.000	0.467	0.000
2. Equatorial Upwelling Systems (EUS)	Atlantic Equatorial Upwelling	0.101	0.090	0.079	0.606	0.540	0.474	0.000	0.000	0.000
	Pacific Equatorial Upwelling	0.079	0.071	0.065	0.474	0.426	0.39	0.096	0.001	0.071
3. Semi-Enclosed Seas (SES)	Arabian Gulf	0.027	0.099	0.042	0.162	0.594	0.252	0.577	0.305	0.282
	Baltic Sea	0.352	0.165	0.06	2.112	0.99	0.36	0.000	0.155	0.299
	Black Sea	−0.004	0.053	0.139	−0.024	0.318	0.834	0.943	0.683	0.009
	Mediterranean Sea	0.035	0.084	0.110	0.21	0.504	0.660	0.083	0.32	0.006
	Red Sea	0.033	0.07	0.047	0.198	0.42	0.282	0.203	0.138	0.042
4. Coastal Boundary Systems (CBS)	Atlantic Ocean (west)	0.137	0.123	0.127	0.822	0.738	0.762	0.000	0.000	0.000
	Caribbean Sea/Gulf of Mexico	0.023	0.024	0.019	0.138	0.144	0.114	0.193	0.498	0.281
	Indian Ocean (west)	0.097	0.100	0.096	0.582	0.600	0.576	0.000	0.000	0.000
	Indian Ocean (east)	0.099	0.092	0.080	0.594	0.552	0.480	0.000	0.000	0.000
	Indian Ocean (east), Southeast Asia, Pacific Ocean (west)	0.144	0.134	0.107	0.864	0.804	0.642	0.000	0.000	0.000
5. Eastern Boundary Upwelling Ecosystems (EBUE)	Benguela Current	0.062	0.032	0.002	0.372	0.192	0.012	0.012	0.437	0.958
	California Current	0.117	0.122	0.076	0.702	0.732	0.456	0.026	0.011	0.125
	Canary Current	0.054	0.089	0.106	0.324	0.534	0.636	0.166	0.014	0.000
	Humboldt Current	0.051	0.059	0.104	0.306	0.354	0.624	0.285	0.205	0.013
6. Subtropical Gyres (STG)	Indian Ocean	0.141	0.112	0.103	0.846	0.672	0.618	0.000	0.000	0.000
	North Atlantic Ocean	0.042	0.046	0.029	0.252	0.276	0.174	0.048	0.276	0.038
	South Atlantic Ocean	0.079	0.083	0.098	0.474	0.498	0.588	0.000	0.017	0.000
	North Pacific Ocean (west)	0.065	0.071	0.059	0.390	0.426	0.354	0.000	0.018	0.000
	North Pacific Ocean (east)	0.008	0.042	0.051	0.048	0.252	0.306	0.617	0.133	0.014
	North Pacific Ocean	0.034	0.055	0.051	0.204	0.33	0.306	0.001	0.053	0.000
	South Pacific Ocean (west)	0.060	0.076	0.092	0.360	0.456	0.552	0.002	0.000	0.000
	South Pacific Ocean (east)	0.055	0.056	0.088	0.330	0.336	0.528	0.000	0.058	0.000
	South Pacific Ocean	0.056	0.060	0.089	0.336	0.360	0.534	0.000	0.027	0.000

Continued next page →

Table 30-1 (continued)

	Sub-region	Regression slope			Total change over 60 years			*p*-value, slope different from zero		
		°C per decade (coolest month)	°C per decade (all months)	°C per decade (warmest month)	Change over 60 years (coolest month)	Change over 60 years (all months)	Change over 60 years (warmest month)	°C per decade (coolest month)	°C per decade (all months)	°C per decade (warmest month)
Coral Reef Provinces; see Figure 30-4(b)	Caribbean Sea/Gulf of Mexico	0.026	0.024	0.023	0.156	0.144	0.138	0.107	0.382	0.203
	Coral Triangle and Southeast Asia	0.137	0.131	0.098	0.822	0.786	0.588	0.000	0.000	0.000
	Indian Ocean (east)	0.081	0.097	0.116	0.486	0.582	0.696	0.000	0.000	0.000
	Indian Ocean (west)	0.091	0.100	0.102	0.546	0.600	0.612	0.000	0.000	0.000
	Pacific Ocean (east)	0.079	0.094	0.101	0.474	0.564	0.606	0.106	0.000	0.023
	Pacific Ocean (west)	0.072	0.073	0.073	0.432	0.438	0.438	0.000	0.000	0.000
Basin Scale	North Atlantic Ocean	0.045	0.061	0.090	0.270	0.366	0.540	0.002	0.198	0.000
	South Atlantic Ocean	0.076	0.074	0.101	0.456	0.444	0.606	0.000	0.041	0.000
	Atlantic Ocean	0.060	0.068	0.091	0.360	0.408	0.546	0.000	0.000	0.000
	North Pacific Ocean	0.030	0.052	0.046	0.180	0.312	0.276	0.000	0.248	0.006
	South Pacific Ocean	0.055	0.048	0.075	0.330	0.288	0.450	0.000	0.115	0.000
	Pacific Ocean	0.043	0.052	0.046	0.258	0.312	0.276	0.000	0.000	0.006
	Indian Ocean	0.130	0.108	0.106	0.780	0.648	0.636	0.000	0.000	0.000

are complicated by the influence of patterns of long-term variability and by the small size and land-locked nature of SES. Coastal Boundary Systems (except the Caribbean and Gulf of Mexico) all showed highly significant (p-value ≤ 0.05) warming (0.09°C to 0.13°C per decade; Table 30-1). Among the EBUE, the Canary and Californian Current regions exhibited a significant rate of change in the average SST (0.09°C per decade and 0.12°C per decade, respectively; p-value ≤ 0.05), while the Benguela and Humboldt Currents did not show significant temperature changes from 1950 to 2009 (p-value ≤ 0.05; Table 30-1). There was some variability between EUBEs in terms of the behavior of the coolest and warmest months. The temperature of the coolest month increased significantly from 1950 to 2009 in the case of the Benguela and California Currents (0.06°C per decade and 0.12°C per decade, respectively; p-value ≤ 0.05), while there was a significant increase in the temperature of the warmest month in the case of the Canary and Humboldt Currents (0.11°C per decade and 0.10°C per decade, respectively; Table 30-1).

The average temperature of STG showed complex patterns with increasing temperatures (1950–2009) in the Indian, South Atlantic, and South Pacific Oceans (*very likely*; 0.11°C, 0.08°C, and 0.06°C per decade, respectively; p-value ≤ 0.05), but not in the North Atlantic or North Pacific Ocean (p-value ≤ 0.05). These rates are half the value reported over shorter periods (e.g., 1998–2010; Table 1 in Signorini and McClain, 2012) and based on NOAA_OI_SST_V2 data. Given the sensitivity of coral reefs to temperature (Eakin et al., 2010; Strong et al., 2011; Lough, 2012; Box CC-CR), trends in key coral reef regions were also examined using the World Resources Institute's Reefs at Risk report (www.wri.org) to identify HadISST1.1 grid cells containing coral reefs (Figure 30-4b). Grouping the results into six major coral reef regions, coral reef waters (with the notable exception of the Gulf of Mexico and Caribbean) were found to show strong increases in average temperature (0.07°C to 0.13°C per decade) as well as the temperature of the coolest (0.07°C to 0.14°C decade) and warmest months (*very likely*) (0.07°C to 0.12°C per decade; Table 30-1). These trends in temperature have resulted in an absolute increase in sea temperature of 0.44°C to 0.79°C from 1950 to 2009.

Given the essential role that temperature plays in the biology and ecology of marine organisms (Box CC-MB; Sections 6.2-3; Pörtner, 2002; Poloczanska et al., 2013), the speed of isotherm migration ultimately determines the speed at which populations must either move, adapt, or acclimate to changing sea temperatures (Pörtner, 2002; Burrows et al., 2011; Hoegh-Guldberg, 2012). Burrows et al. (2011) calculated the rate at which isotherms are migrating as the ratio of the rate of SST change (°C yr^{-1}) to the spatial gradient of temperature (°C km^{-1}) over the period 1960–2009 (Figure 30-3). Although many of these temperature trajectories are toward the polar regions, some are not and are influenced by features such as coastlines. This analysis and others (e.g., North Atlantic; González-Taboada and Anadón, 2012) reveals that isotherms in the Ocean are moving at high velocities (to over 200 km per decade), especially at low latitudes (*high confidence*; Figure 30-3). Other sub-regions showed smaller velocities with contracting isotherms (cooling) in some areas (e.g., the Central and North Pacific, and Atlantic Oceans; Figure 30-3). There are also changes in the timing of seasonal temperatures in both spring and fall/autumn (Burrows et al., 2011; Poloczanska et al., 2013), which, together with other variables (e.g., light, food availability, geography), are *likely* to affect biological processes such as the migration of species to higher latitudes, and the timing and synchrony of reproductive and other seasonal behaviors.

Excursions of sea temperature above long-term summer temperature maxima (or below long-term temperature minima) significantly affect marine organisms and ecosystems (Hoegh-Guldberg, 1999; Bensoussan et al., 2010; Crisci et al., 2011; Harley, 2011). Consequently, calculating heat stress as a function of exposure time and size of a particular temperature anomaly is useful in understanding recent changes to

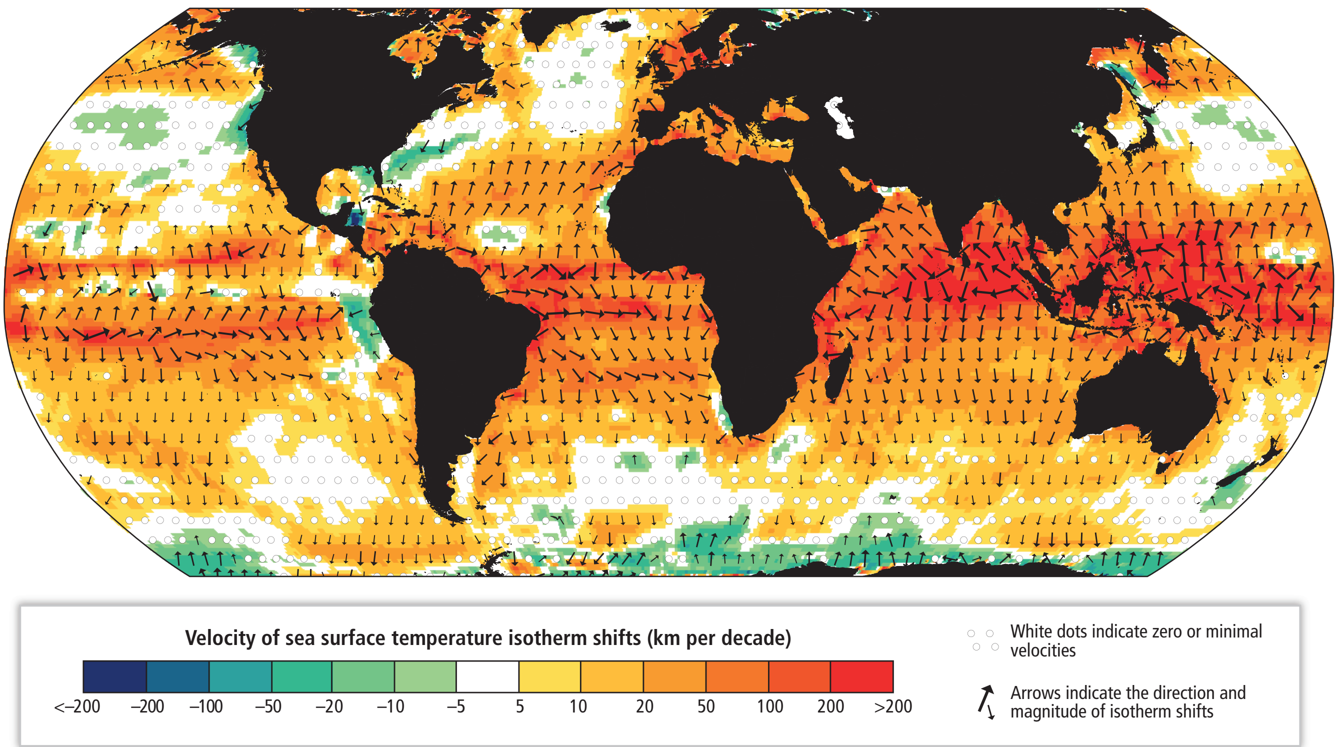


Figure 30-3 | Velocity at which sea surface temperature (SST) isotherms shifted (km per decade) over the period 1960–2009 calculated using Hadley Centre Interpolated sea surface temperature 1.1 (HadISST1.1), with arrows indicating the direction and magnitude of shifts. Velocity of climate change is obtained by dividing the temperature trend in °C per decade by the local spatial gradient °C km^{-1}. The direction of movement of SST isotherms are denoted by the direction of the spatial gradient and the sign of the temperature trend: toward locally cooler areas with a local warming trend or toward locally warmer areas where temperatures are cooling. Adapted from Burrows et al., 2011.

organisms and ecosystems (e.g., coral reefs and thermal anomalies; 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) as the running total over 4 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 accumulated heat stress (Figure 30-4a). These are areas rich in thermally sensitive coral reefs (Figure 30-4b; Strong et al., 2011). There was also a higher proportion of years that have had at least one stress event (DHM > 1) in the last 30 years (1981–2010, Figure 30-4c) than in the preceding 30 years (1951–1980; Figure 30-4c,d).

The three ocean basins will continue warming under moderate (RCP4.5) to high (RCP8.5) emission trajectories (*high confidence*) and will only stabilize over the second half of the century in the case of low range scenarios such as RCP2.6 (Figure 30-2e,f,g; WGI AR5 AI.4–AI.8). Projected changes were also examined for specific ocean sub-regions using ensemble averages from Atmosphere-Ocean General Circulation Models (AOGCM) simulations available in the Coupled Model Intercomparison Project Phase 5 (CMIP5) archive (Table SM30-3) for the four scenarios of the future (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 SM30-3). The subset of CMIP5 models were chosen because each has historic runs enabling the derivation of the maximum monthly mean (MMM) climatology from 1985 to 2000, ensuring that all anomalies were comparable across time periods and across RCPs (Figure 30-10). Model hind-cast changes matched those observed for ocean sub-regions for the period 1980–2009 (HadISST1.1; 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-value ≤ 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 SM30-4). In the near term, changes in the temperature projected for the surface layers of the Ocean were largely indistinguishable between the different RCP scenarios owing to the similarity in forcing up to 2040. By the end of the century, however, SSTs across the ocean sub-regions were 1.8°C to 3.3°C higher under RCP8.5 than those projected to occur under RCP2.6 (Table SM30-4; Figure 30-2e,f,g). The implications of these projected changes on the structure and function of oceanic systems are discussed below.

30.3.1.2. Sea Level

The rate of sea level rise (SLR) since the mid-19th century has been larger than the mean rate during the previous two millennia (*high confidence*). Over the period 1901–2010, global mean sea level (GMSL) rose by 0.19 (0.17 to 0.21) m (WGI AR5 Figure SPM.3; WGI AR5 Sections 3.7, 5.6, 13.2). It is *very likely* that the mean rate of global averaged SLR was 1.7 (1.5 to 1.9) mm yr^{-1} between 1901 and 2010, 2.0 (1.7 to 2.3) mm yr^{-1}

between 1971 and 2010, and 3.2 (2.8 to 3.6) mm yr^{-1} between 1993 and 2010 (WGI AR5 SPM, Section 3.7). These observations are consistent with thermal expansion of the Ocean due to warming plus the addition of water from loss of mass by melting glaciers and ice sheets. Current rates of SLR vary geographically, and can be higher or lower than the GMSL for several decades at time due to fluctuations in natural variability and ocean circulation (Figure 30-5). For example, rates of SLR are up to three times higher than the GMSL in the Western Pacific and Southeast Asian region, and decreasing in many parts of the Eastern Pacific for the period 1993–2012 as measured by satellite altimetry (Figure 30-5; WGI AR5 Section 13.6.5).

SLR under increasing atmospheric GHG concentrations will continue for hundreds of years, with the extent and rate of the increase in GMSL being dependent on the emission scenario. Central to this analysis is the millennial-scale commitment to further SLR that is *likely* to arise from the loss of mass of the Greenland and Antarctic ice sheets (WGI AR5 Section 13.5.4, Figure 13.13). SLR is *very likely* to increase during the 21st century relative to the period 1971–2010 due to increased ocean warming and the continued contribution of water from loss of mass from glaciers and ice sheets. There is *medium confidence* that median SLR by 2081–2100 relative to 1986–2005 will be (5 to 95% range of process-based models): 0.44 m for RCP2.6, 0.53 m for RCP4.5, 0.55 m for RCP6.0, and 0.74 m for RCP8.5. Higher values of SLR are possible but are not backed by sufficient evidence to enable reliable estimates of the probability of specific outcomes. Many semi-empirical model projections of GMSL rise are higher than process-based model projections (up to about twice as large), but there is no consensus in the scientific community about their reliability and there is thus *low confidence* in their projections (WGI AR5 Sections 13.5.2, 13.5.3, Table 13.6, Figure 13.12).

It is considered *very likely* that increases in sea level will result in greater levels of coastal flooding and more frequent extremes by 2050 (WGI AR5 Section 13.7.2; IPCC, 2012). It is *about as likely as not* that the frequency of the most intense storms will increase in some ocean basins,

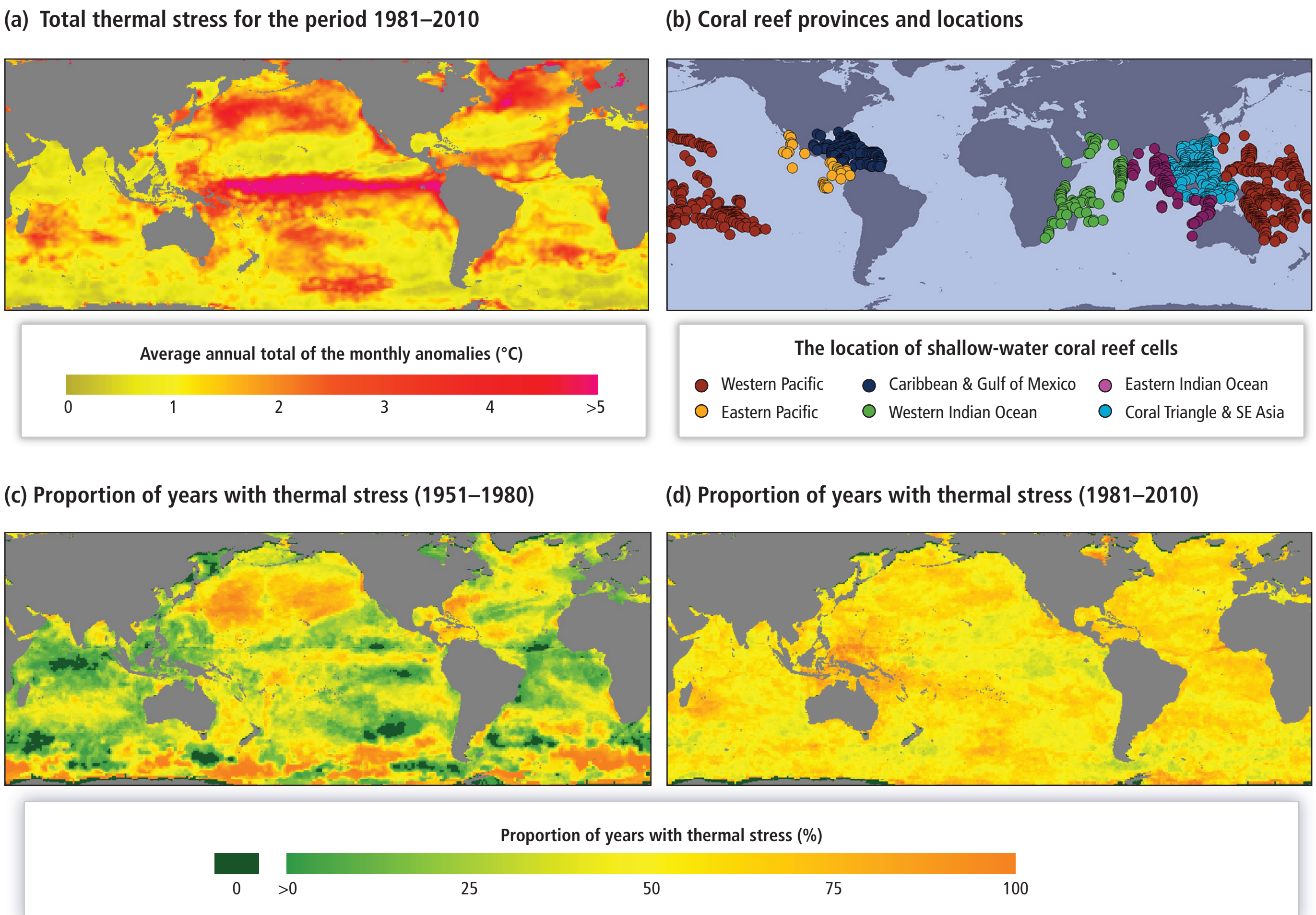


Figure 30-4 | Recent changes in thermal stress calculated using Hadley Centre Interpolated sea surface temperature data (HadISST1.1). A monthly climatology was created by averaging the HadISST monthly SST values over a reference period of 1985–2000 to create 12 averages, one for each month of the year. The Maximum Monthly Mean climatology was created by selecting the hottest month for each pixel. Anomalies were then created by subtracting this value from each sea surface temperature value, but allowing values to be recorded only if they were greater than zero (Donner et al., 2007). Two measures of the change in thermal stress were calculated as a result: The total thermal stress for the period 1981–2010, calculated by summing all monthly thermal anomalies for each grid cell (a); and the proportion of years with thermal stress, which is defined as any year that has a thermal anomaly, for the periods 1951–1980 (c) and 1981–2010 (d). The location of coral reef grid cells used in Table 30-1 and for comparison to regional heat stress is depicted in (b). Each dot is positioned over a 1 × 1 degree grid cell within which lies at least one carbonate coral reef. The latitude and longitude of each reef is derived from data provided by the World Resources Institute's Reefs at Risk report (http://www.wri.org). The six regions are as follows: red—Western Pacific Ocean; yellow—Eastern Pacific Ocean; dark blue—Caribbean and Gulf of Mexico; green—Western Indian Ocean; purple—Eastern Indian Ocean; and light blue—Coral Triangle and Southeast Asia.

although there is *medium agreement* that the global frequency of tropical cyclones is *likely* to decrease or remain constant (WGI AR5 Sections 14.6, 14.8). Although understanding of associated risks is relatively undeveloped, coastal and low-lying areas, particularly in southern Asia, as well as the Pacific Ocean and North Atlantic regions, face increased flood risk (Sections 5.3.3.2, 8.2.3.3, 9.3.4.3). Future impacts of SLR include increasing penetration of storm surges into coastal areas and changing patterns of shoreline erosion (Section 5.3), as well as the inundation of coastal aquifers by saltwater (Sections 5.4.2.5, 29.3.2). Regionally, some natural ecosystems may reduce in extent (e.g., mangroves), although examples of habitat expansion have been reported (Brown et al., 2011). Overall, changes to sea level are *very likely* to modify coastal ecosystems such as beaches, salt marshes, coral reefs, and mangroves (Section 5.4.2; Box CC-CR), especially where rates of sea level rise are highest (e.g., Southeast Asia and the Western Pacific).

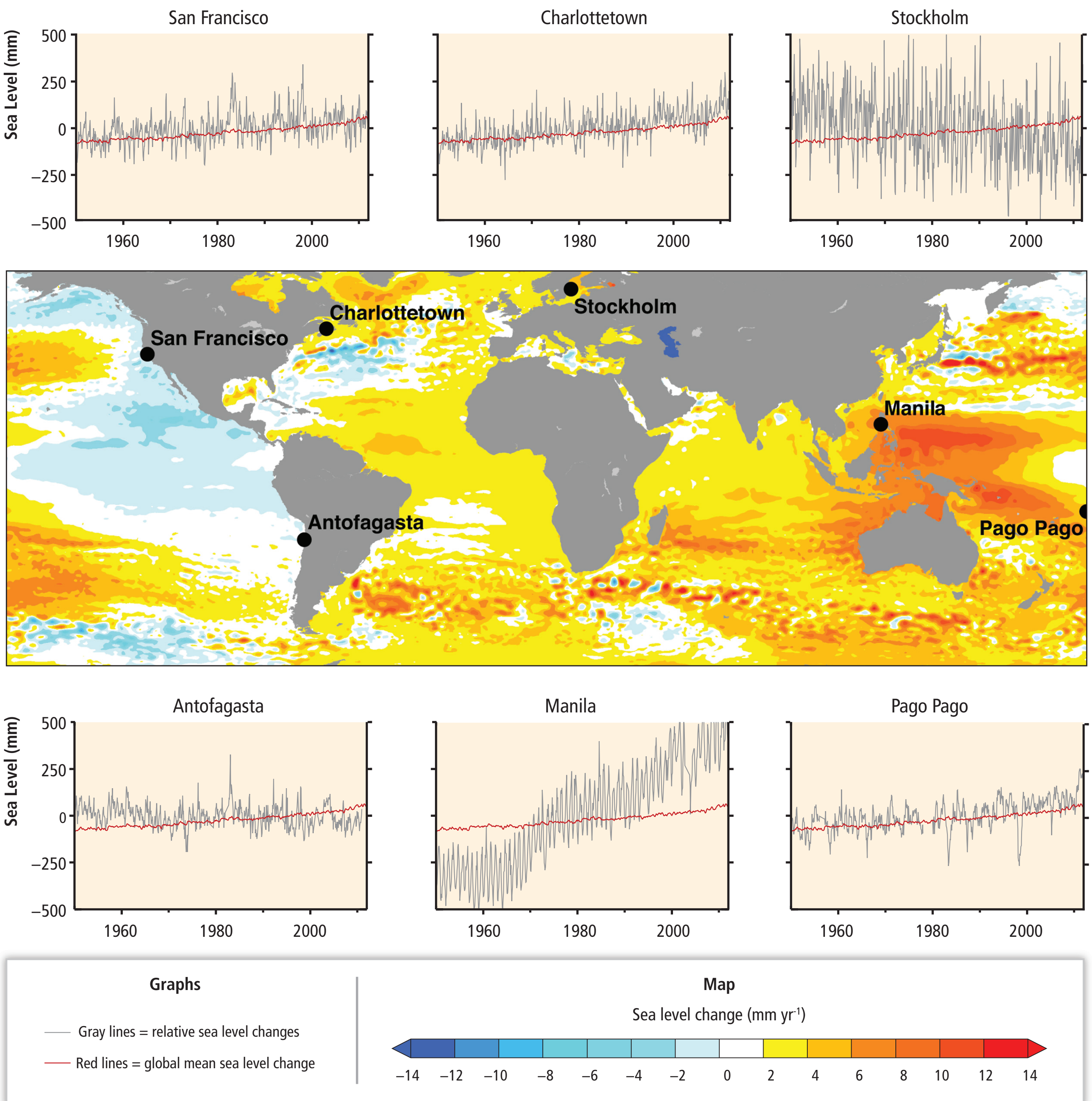


Figure 30-5 | Map of the rate of change in sea surface height (geocentric sea level) for the period 1993–2012 derived from satellite altimetry. Also shown are relative sea level changes (gray lines) from selected tide gauge stations for the period 1950–2012. For comparison, an estimate of global mean sea level change is shown (red lines) with each tide gauge time series. The relatively large short-term oscillations in local sea level (gray lines) are due to the natural climate variability and ocean circulation. For example, the large regular deviations at Pago Pago are associated with the El Niño-Southern Oscillation. Figure originally presented in WGI AR5 FAQ 13.1, Figure 1.

30.3.1.3. Ocean Circulation, Surface Wind, and Waves

Circulation of atmosphere and ocean (and their interactions) drives much of the chemical, physical, and biological characteristics of the Ocean, shaping phenomena such as ocean ventilation, coastal upwelling, primary production, and biogeochemical cycling. Critical factors for transporting nutrients from deep waters to the marine primary producers in the upper layers of the ocean include wind-driven mixing and upwelling.

There has been a poleward movement of circulation features, including a widening of the tropical belt, contraction of the northern polar vortex, and a shift of storm tracks and jet streams to higher latitudes (*medium confidence*; WGI AR5 Sections 2.7.5-6, 2.7.8; WGI AR5 Box 2.5). Long-term patterns of variability (years to decades) continue to prevent robust conclusions regarding long-term changes in atmospheric circulation and winds in many cases (WGI AR5 Section 2.7.5). There is *high confidence*, however, that the increase in northern mid-latitude westerly winds from the 1950s to the 1990s, and the weakening of the Pacific Walker Circulation from the late 19th century to the 1990s, have been largely offset by recent changes (WGI AR5 Sections 2.7.5, 2.7.8; WGI AR5 Box 2.5). Wind stress has increased since the early 1980s over the Southern Ocean (*medium confidence*; WGI AR5 Section 3.4.4), and tropical Pacific since 1990 (*medium confidence*), while zonal mean wind stress may have declined by 7% in the equatorial Pacific from 1862–1990 due to weakening of the tropical Walker Circulation (*medium confidence*; WGI AR5 Section 3.4.4; Vecchi et al., 2006). For example, it is *very likely* that the subtropical gyres of the major ocean basins have expanded and strengthened since 1993. However, the short-term nature of observing means that these changes are *as likely as not* to be due to decadal variability and/or due to longer term trends in wind forcing associated with climate change (WGI AR5 Section 3.6). Other evidence of changes in ocean circulation is limited to relatively short-term records that suffer from low temporal and spatial coverage. Therefore, there is *very low confidence* that multi-decadal trends in ocean circulation can be separated from decadal variability (WGI AR5 Section 3.6.6). There is no evidence of a long-term trend in large-scale currents such as the Atlantic Meridional Overturning Circulation (AMOC), Indonesian Throughflow (ITF), the Antarctic Circumpolar Current (ACC), or the transport of water between the Atlantic Ocean and Nordic Seas (WGI AR5 Section 3.6; WGI AR5 Figures 3.10, 3.11).

Wind speeds may have increased within the regions of EBUE (*low confidence* in attribution to climate; e.g., California Current, WGI AR5 Section 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 there is *low agreement* as to whether or not upwelling will intensify or not under rapid climate change (Bakun, 1990; Bakun et al., 2010; Box CC-UP).

Surface waves are influenced by wind stress, although understanding trends remains a challenge due to limited data. There is *medium confidence* that significant wave height (SWH) has increased since the mid-1950s over much of the North Atlantic north of 45°N, with typical winter season trends of up to 20 cm per decade (WGI AR5 Section 3.4.5). There is *low confidence* in the current understanding of how SWH will change over the coming decades and century for most of the Ocean. It remains an important knowledge gap (WGI AR5 Section 3.4).

30.3.1.4. Solar Insolation and Clouds

Solar insolation plays a crucially important role in the biology of many marine organisms, not only as a source of energy for photosynthesis but also as a potential co-stressor in the photic zone (with temperature), as is seen during mass coral bleaching and mortality events (e.g., Hoegh-Guldberg, 1999). Global surface solar insolation (from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) Reanalysis Project; Kalnay et al., 1996) decreased by 4.3 W m^{-2} per decade from the 1950s until 1991, after which it increased at 3.3 W m^{-2} per decade until 1999 (Ohmura, 2009; Wild, 2009), matching a broad suite of evidence from many land-based sites (WGI AR5 Section 2.3.3). Although there is consistency between independent data sets for particular regions, there is substantial ambiguity and therefore *low confidence* in observations of global-scale cloud variability and trends (WGI AR5 Section 2.5.6). There is also *low confidence* in projections of how cloudiness, solar insolation, and precipitation will change as the planet warms due to the large interannual and decadal variability (El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO)), short observation time series, and uneven spatial sampling, particularly in the early record (before 1950; WGI AR5 Section 2.5.8).

30.3.1.5. Storm Systems

As agents of water column mixing, storms (from small atmospheric disturbances to intense tropical cyclones) 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). Large storms can destroy coastal infrastructure and coastal habitats such as coral reefs and mangrove forests, which can take decades to recover (Lotze et al., 2011; De'ath et al., 2012).

Although there is *low confidence* for long-term trends in tropical cyclone activity globally (largely due to the lack of reliable long-term data sets), it is *virtually certain* that the frequency and intensity of the strongest tropical cyclones in the North Atlantic have increased since the 1970s (WGI AR5 Section 2.6.3). There is *medium agreement* that the frequency of the most intense cyclones in the Atlantic has increased since 1987 (WGI AR5 Section 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). It is also *likely* that there has been a decrease in the number of land-falling tropical cyclones along the East Australian coast since the 19th century (WGI AR5 Section 2.6.3; Callaghan and Power, 2011). It is *likely* that these patterns are influenced by interannual variability such as ENSO, with land-falling tropical 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 extratropical cyclone systems since the 1950s in the North Pacific. Similar trends have been reported for the Asian region, although analyses are limited in terms of the spatial and temporal coverage of reliable records (WGI AR5 Section 2.6.4). There is *low confidence*, however, in large-scale trends in storminess or storminess proxies over the last century owing to the lack of long-term data and inconsistencies between studies (WGI AR5 Section 2.6.4).

30.3.1.6. Thermal Stratification

As heat has accumulated in the Ocean there has been a 4% increase in thermal stratification of the upper layers in most ocean regions (0 to 200 m, 40-year record) north of 40°S (WGI AR5 Section 3.2.2). Increasing thermal stratification has reduced ocean ventilation and the depth of mixing in many ocean sub-regions (*medium confidence*; WGI AR5 Section 3.8.3). This in turn reduces the availability of inorganic nutrients and consequently primary productivity (*medium confidence*; Section 6.3.4). In the STG, which dominate the three major ocean basins (Section 30.5.6), satellite-derived estimates of surface chlorophyll and primary production decreased between 1999 and 2007 (Box CC-PP). In contrast, however, *in situ* observations at fixed stations in the North Pacific and North Atlantic Oceans (Hawaii Ocean Time-series (HOT) and Bermuda Atlantic Time-series Study (BATS)) showed increases in nutrient and chlorophyll levels and primary production over the same period, suggesting that other processes (e.g., ENSO, PDO, North Atlantic Oscillation (NAO), winds, eddies, advection) can counteract broad-scale trends at local scales (Box CC-PP). The continued warming of the surface layers of the Ocean will *very likely* further enhance stratification and potentially limit the nutrient supply to the euphotic zone in some areas. 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 CC-UW).

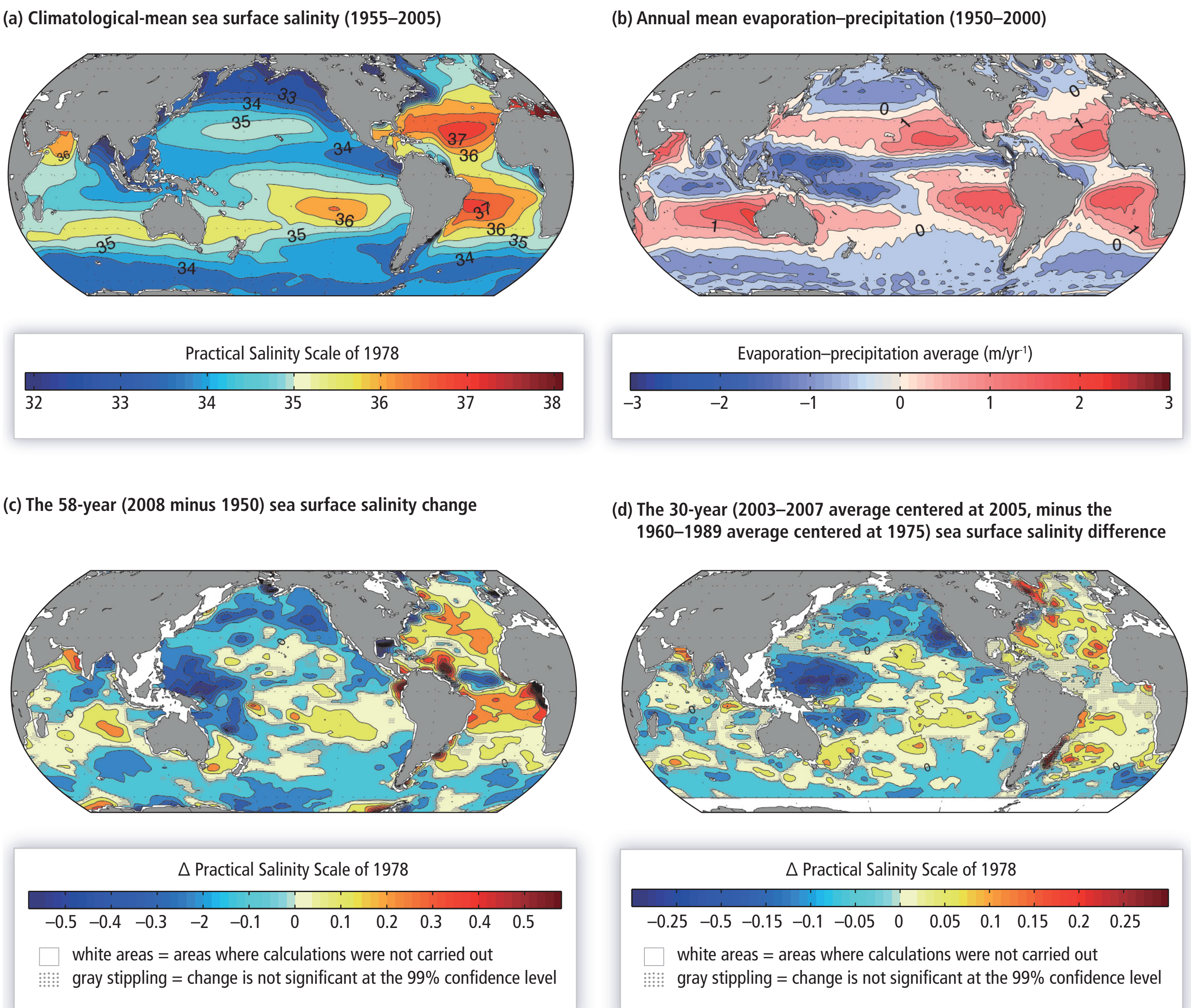


Figure 30-6 | (a) The 1955–2005 climatological-mean sea surface salinity (Antonov et al., 2010) color contoured at 0.5 Practical Salinity Scale 1978 (PSS78) intervals (black lines). (b) Annual mean evaporation-precipitation averaged over the period 1950–2000 (National Centers for Environmental Prediction (NCEP)) color contoured at 0.5 m yr–1 intervals (black lines). (c) The 58-year (2008 minus 1950) sea surface salinity change derived from the linear trend (PSS78), with seasonal and El Niño-Southern Oscillation (ENSO) signals removed (Durack and Wijffels, 2010) color contoured at 0.116 PSS78 intervals (black lines). (d) The 30-year (2003–2007 average centered at 2005, minus the 1960–1989 average centered at 1975) sea surface salinity difference (PSS78) (Hosoda et al., 2009) color contoured at 0.06 PSS78 intervals (black lines). Contour intervals in (c) and (d) are chosen so that the trends can be easily compared, given the different time intervals in the two analyzes. White areas in (c) and (d) are marginal seas where the calculations are not carried out. Regions where the change is not significant at the 99% confidence level are stippled in gray. Figure originally presented as WGI AR5 Figure 3.4. All salinity values quoted in the chapter are expressed on the Practical Salinity Scale 1978 (PSS78) (Lewis and Fofonoff, 1979).

30.3.2. Chemical Changes

30.3.2.1. Surface Salinity

The global water cycle is dominated by evaporation and precipitation occurring over ocean regions, with surface ocean salinity varying with temperature, solar radiation, cloud cover, and ocean circulation (Deser et al., 2004). Changes in salinity influence stratification of water masses and circulation. Ocean salinity varies regionally (Figure 30-6a) and is a function of the balance between evaporation and precipitation (Durack and Wijffels, 2010; WGI AR5 Section 3.3). Evaporation-dominated regions (Figure 30-6b) such as the STG and Atlantic and Western Indian Oceans (WGI AR5 Section 3.3.3) have elevated salinity, while areas of high precipitation such as the North Pacific, northeastern Indian Ocean, Southeast Asia, and the eastern Pacific have relatively low salinities (WGI AR5 Section 3.3.3; Figure 30-6a). It is *likely* that large-scale trends in salinity have also occurred in the Ocean interior, deriving from changes to salinity at the surface and subsequent subduction (WGI AR5 Section 3.3).

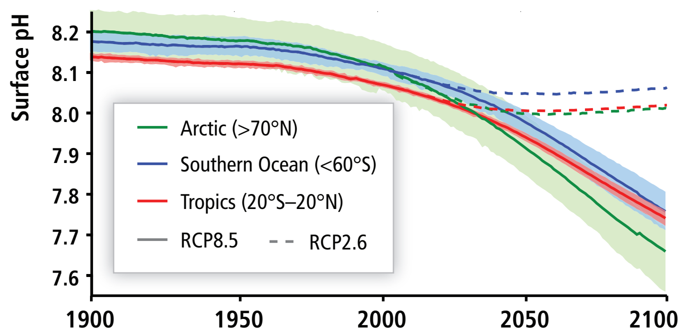
Salinity trends are consistent with the amplification of the global hydrological cycle (Durack et al., 2012; Pierce et al., 2012), a consequence of a warmer atmosphere *very likely* producing the observed trend in greater precipitation, evaporation, atmospheric moisture (Figure 30-6b), and extreme events (WGI AR5 Sections 2.6.2.1, 3.3.4; IPCC, 2012). Spatial patterns in salinity and evaporation-precipitation are correlated, providing indirect evidence that these processes have been enhanced since the 1950s (WGI AR5 Sections 3.3.2-4; WGI AR5 Figures 3.4, 3.5, 3.20d; WGI AR5 FAQ 3.3). These trends in salinity are *very likely* to have a discernible contribution from anthropogenic climate change (WGI AR5 Section 10.4.2). The combined changes in surface 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; Figure 30-6c,d) or external to it (e.g., solar forcing or volcanic eruptions; Pierce et al., 2012). There is *high confidence* between climate models that the observed trends in ocean salinity will continue as average global temperature increases (Durack and Wijffels, 2010; Terray et al., 2012). Ramifications of these changes are largely unknown but are of interest given the role of ocean salinity and temperature in fundamental processes such as the AMOC.

30.3.2.2. Ocean Acidification

The Ocean has absorbed approximately 30% of atmospheric CO_2 from human activities, resulting in decreased ocean pH and carbonate ion concentrations, and increased bicarbonate ion concentrations (Box CC-OA; WGI AR5 Box 3.2; WGI AR5 Figure SM30-2). The chemical response to increased CO_2 dissolving into the Ocean from the atmosphere is known with *very high confidence* (WGI AR5 Section 6.4.4). Factors such as temperature, biological processes, and sea ice (WGI AR5 Section 6.4) play significant roles in determining the saturation state of seawater for polymorphs (i.e., different crystalline forms) of calcium carbonate. Consequently, pH and the solubility of aragonite and calcite are naturally lower at high latitudes and in upwelling areas (e.g., California Current EBUE), where organisms and ecosystems may be relatively more exposed to ocean acidification as a result (Feely et al., 2012; Gruber et al., 2012; Figures 30-7a,b, SM30-2). Aragonite and calcite concentrations vary with depth, with under-saturation occurring at deeper depths in the Atlantic (calcite: 3500 to 4500 m, aragonite: 400 to 3000 m) as opposed to the Pacific and Indian Oceans (calcite: 100 to 3000 m, aragonite: 100 to 1200 m; Feely et al., 2004, 2009; Orr et al., 2005; Figure 30-8).

Surface ocean pH has decreased by approximately 0.1 pH units since the beginning of the Industrial Revolution (*high confidence*) (Figure 30-7a; WGI AR5 Section 3.8.2; WGI AR5 Box 3.2), with pH decreasing at the rate of –0.0013 and 0.0024 pH units yr^{-1} (WGI AR5 Section 3.8.2; WGI AR5 Table 3.2). The presence of anthropogenic CO_2 diminishes with

(a) Surface pH



(b) Change in surface pH in 2090s from 1990s (RCP8.5)

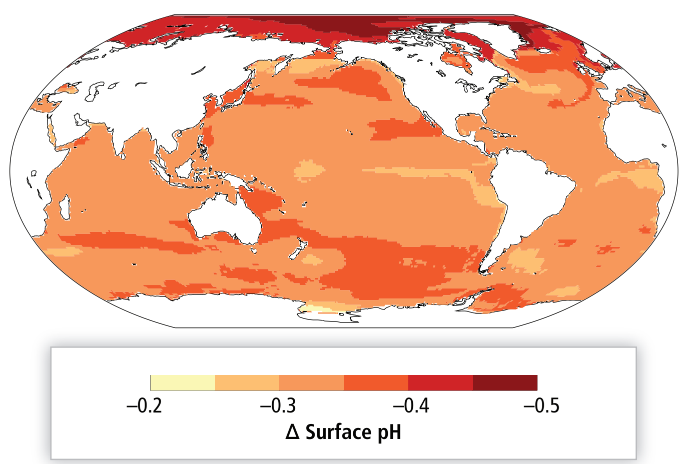


Figure 30-7 | Projected ocean acidification from 11 Coupled Model Intercomparison Project Phase 5 (CMIP5) Earth System models under RCP8.5 (other Representative Concentration Pathway (RCP) scenarios have also been run with the CMIP5 Models): (a) Time series of surface pH shown as the mean (solid line) and range of models (shaded area), given as area-weighted averages over the Arctic Ocean (green), the tropical oceans (red), and the Southern Ocean (blue). (b) Maps of the median model's change in surface pH from 1990s. Panel (a) also includes mean model results from RCP2.6 (dashed lines). Over most of the Ocean, gridded data products of carbonate system variables are used to correct each model for its present-day bias by subtracting the model-data difference at each grid cell following (Orr et al., 2005). Where gridded data products are unavailable (Arctic Ocean, all marginal seas and the Ocean near Indonesia), the results are shown without bias correction. The bias correction reduces the range of model projections by up to a factor of four; for example, in panel (a) compare the large range of model projections for the Arctic (without bias correction) to the smaller range in the Southern Ocean (with bias correction). Figure originally presented in WGI AR5 Figure 6.28.

depth. The saturation horizons of both polymorphs of calcium carbonate, however, are shoaling rapidly (1 to 2 m yr^{-1}, and up to 5 m yr^{-1} in regions such as the California Current (Orr et al., 2005; Feely et al., 2012). Further increases in atmospheric CO_2 are *virtually certain* to further acidify the Ocean and change its carbonate chemistry (Figures SM30-2, 30-7, 30-8). Doubling atmospheric CO_2 (~RCP4.5; Rogelj et al., 2012) will decrease ocean pH by another 0.1 unit and decrease carbonate ion concentrations by approximately 100 µmol kg^{-1} in tropical oceans (Figure 30-8a) from the present-day average of 250 µmol kg^{-1} (*high confidence*). Projected changes for the open Ocean by 2100 (Figures 30-7, 30-8) range from a pH change of –0.14 unit with RCP2.6 (421 ppm CO_2, +1°C, 22% reduction of carbonate ion concentration) to a pH change of –0.43 unit with RCP8.5

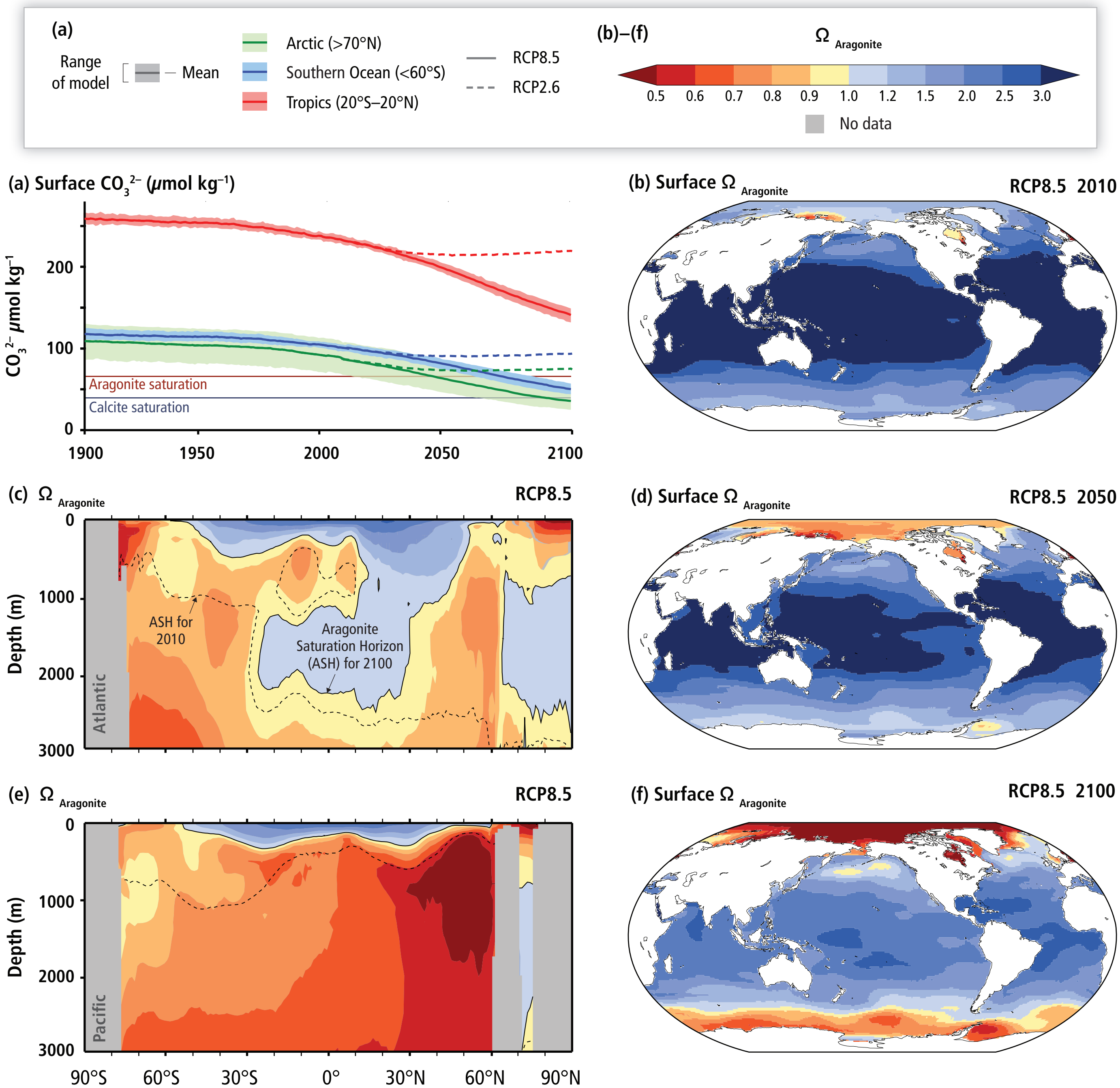


Figure 30-8 | Projected aragonite saturation state ($\Omega_{Aragonite}$) from 11 Coupled Model Intercomparison Project Phase 5 (CMIP5) Earth System Models under Representative Concentration Pathway 8.5 (RCP8.5) scenario. (a) Time series of surface carbonate ion (CO_3^{2-}) concentration shown as the mean (solid line) and range of models (shaded area), given as area-weighted averages over the Arctic Ocean (green), the tropical oceans (red), and the Southern Ocean (blue); maps of the median model's surface $\Omega_{Aragonite}$ in (b) 2010, (d) 2050, and (f) 2100; and zonal mean sections (latitude vs. depth) of $\Omega_{Aragonite}$ in 2100 over (c) the Atlantic Ocean and (e) the Pacific Ocean, while the ASH (Aragonite Saturation Horizon) is shown for 2010 (dotted line) and 2100 (solid line). Panel (a) also includes mean model results from RCP2.6 (dashed lines). As for Figure 30-7, gridded data products of carbonate system variables (Key et al., 2004) are used to correct each model for its present-day bias by subtracting the model-data difference at each grid cell following Orr et al. (2005). Where gridded data products are unavailable (Arctic Ocean, all marginal seas, and the Ocean near Indonesia), results are shown without bias correction. Figure originally presented in WGI AR5 Figure 6.29.

(936 ppm CO_2, +3.7°C, 56% reduction of carbonate ion concentration). The saturation horizons will also become significantly shallower in all oceans (with the aragonite saturation horizon between 0 and 1500 m in the Atlantic Ocean and 0 and 600 m (poles vs. equator) in the Pacific Ocean; Sabine et al., 2004; Orr et al., 2005; WGI AR5 Section 6.4.4; WGI AR5 Figure 6.28). Trends toward under-saturation of aragonite and calcite will also partly depend on ocean temperature, with surface polar waters expected to become seasonally under-saturated with respect to aragonite and calcite within a couple of decades (Figure 30-8c,d,e,f; Box CC-OA; McNeil and Matear, 2008).

Overall, observations from a wide range of laboratory, mesocosm, and field studies reveal that marine macro-organisms and ocean processes are sensitive to the levels of ocean acidification projected under elevated atmospheric CO_2 (*high confidence*; Box CC-OA, Section 6.3.2; Munday et al., 2009; Kroeker et al., 2013). Ecosystems that are characterized by high rates of calcium carbonate deposition (e.g., coral reefs, calcareous 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 (Hoegh-Guldberg et al., 2007; Manzello et al., 2008; Fabricius et al., 2011; Andersson and Gledhill, 2013; Dove et al., 2013) and restructuring of food webs at relatively small (~50 ppm) additional increases in atmospheric CO_2. Projected shoaling of the aragonite and calcite saturation horizons are *likely* to impact deep water (100 to 2000 m) communities of scleractinian corals and other benthic organisms as atmospheric CO_2 increases (Orr et al., 2005; Guinotte et al., 2006; WGI AR5 Section 6.4.4), although studies from the Mediterranean and seamounts off southwest Australia report that some deep water corals may be less sensitive (Thresher et al., 2011; Maier et al., 2013). Organisms are also sensitive to changes in pH with respect to physiological processes such as respiration and neural function (Section 6.3.2). Owing to the relatively short history, yet growing effort, to understand the implications of rapid changes in pH and ocean carbonate chemistry, there are a growing number of organisms and processes reported to be sensitive. The impact of ocean acidification on marine organisms and ecosystems continues to raise serious scientific concern, especially given that the current rate of ocean acidification (at least 10 to 100 times faster than the recent glacial transitions (Caldeira and Wickett, 2003; Hoegh-Guldberg et al., 2007)) is unprecedented within the last 65 Ma (*high confidence*; Ridgwell and Schmidt, 2010) and possibly 300 Ma of Earth history (*medium confidence*; Hönisch et al., 2012; Section 6.1.2).

30.3.2.3. Oxygen Concentration

Dissolved O_2 is a major determinant of the distribution and abundance of marine organisms (Section 6.3.3). Oxygen concentrations vary across ocean basins and are lower in the eastern Pacific and Atlantic basins, and northern Indian Ocean (Figure 30-9b; Section 6.1.1.3). In contrast, some of the highest concentrations of O_2 are associated with cooler high-latitude waters (Figure 30-9b). There is *high agreement* among analyses providing *medium confidence* that O_2 concentrations have decreased in the upper layers of the Ocean since the 1960s, particularly in the equatorial Pacific and Atlantic Oceans (WGI AR5 Section 3.8.3; WGI AR5 Figure 3.20). A formal fingerprint analysis undertaken by Andrews et al. (2013) concluded that recent decreases in oceanic O_2 are due to external influences (*very likely*). Conversely, O_2 has increased in the North and South Pacific, North Atlantic, and Indian Oceans, and is consistent with greater mixing and ventilation due to strengthening wind systems (WGI AR5 Section 3.8.3). The reduction in O_2 concentration in some areas of the Ocean is consistent with that expected from higher ocean temperatures and a reduction in mixing (increasing stratification) (WGI AR5 Section 3.8.3). Analysis of ocean O_2 trends over time (Helm et al., 2011b) reveals that the decline in O_2 solubility with increased temperature is responsible for no more than 15% of the observed change. The remaining 85%, consequently, is associated with increased deep-sea microbial respiration and reduced O_2 supply due to increased ocean stratification (WGI AR5 Section 6.1.1.3). In coastal areas, eutrophication can lead to increased transport of organic carbon into adjacent ocean habitats where microbial metabolism is stimulated, resulting in a rapid drawdown of O_2 (Weeks et al., 2002; Rabalais et al., 2009; Bakun et al., 2010).

The development of hypoxic conditions (defined as O_2 concentrations below ~60 µmol kg^{-1}) over recent decades has been documented across

Frequently Asked Questions

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

In less than 150 years, greenhouse gas (GHG) emissions have resulted in such major physical and chemical changes in our oceans that it will take thousands of years to reverse them. There are a number of reasons for this. Given its large mass and high heat capacity, the ability of the Ocean to absorb heat is 1000 times larger than that of the atmosphere. The Ocean has absorbed at least nine-tenths of the Earth's heat gain between 1971 and 2010. To reverse that heating, the warmer upper layers of the Ocean have to mix with the colder deeper layers. That mixing can take as much as 1000 years. This means it will take centuries to millennia for deep ocean temperatures to warm in response to today's surface conditions, and at least as long for ocean warming to reverse after atmospheric GHG concentrations decrease (*virtually certain*). But climate change-caused alteration of basic conditions in the Ocean is not just about temperature. The Ocean becomes more acidic as more carbon dioxide (CO_2) enters it and will take tens of thousands of years to reverse these profound changes to the carbonate chemistry of the ocean (*virtually certain*). These enormous physical and chemical changes are producing sweeping and profound changes in marine ecosystems. Large and abrupt changes to these ecosystems are unlikely to be reversible in the short to medium term (*high confidence*).

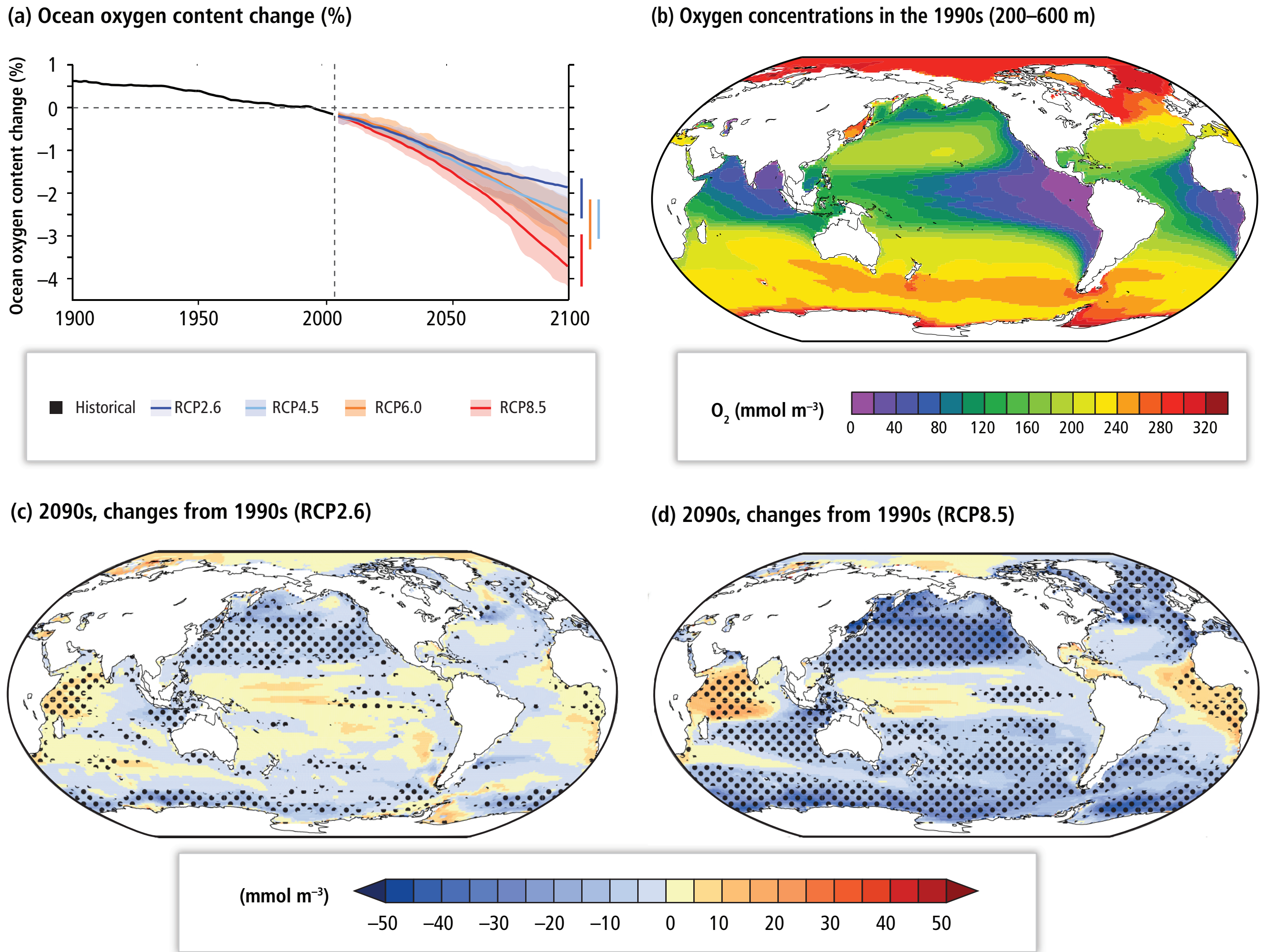


Figure 30-9 | (a) Simulated changes in dissolved O_2 (mean and model range as shading) relative to 1990s for Representative Concentration Pathway 2.6 (RCP2.6), RCP4.5, RCP6.0, and RCP8.5. (b) Multi-model mean dissolved O_2 (mmol m^{-3}) in the main thermocline (200 to 600 m depth average) for the 1990s, and changes in the 2090s relative to 1990s for RCP2.6 (c) and RCP8.5 (d). To indicate consistency in the sign of change, regions are stippled when at least 80% of models agree on the sign of the mean change. These diagnostics are detailed in Cocco et al. (2013) in a previous model intercomparison using the Special Report on Emission Scenarios (SRES)-A2 scenario and have been applied to Coupled Model Intercomparison Project Phase 5 (CMIP5) models here. Models used: Community Earth System Model 1–Biogeochemical (CESM1-BGC), Geophysical Fluid Dynamics Laboratory–Earth System Model 2G (GFDL-ESM2G), Geophysical Fluid Dynamics Laboratory–Earth System Model 2M (GFDL-ESM2M), Hadley Centre Global Environmental Model 2–Earth System (HadGEM2-ES), Institute Pierre Simon Laplace–Coupled Model 5A–Low Resolution (IPSL-CM5A-LR), Institute Pierre Simon Laplace–Coupled Model 5A–Medium Resolution (IPSL-CM5A-MR), Max Planck Institute–Earth System Model–Low Resolution (MPI-ESM-LR), Max Planck Institute–Earth System Model–Medium Resolution (MPI-ESM-MR), Norwegian Earth System Model 1 (Emissions capable) (NorESM1). Figure originally presented in WGI AR5 Figure 6.30.

a wide array of ocean sub-regions including some SES (e.g., Black and Baltic Seas), the Arabian Sea, and the California, Humboldt, and Benguela Current systems, where eruptions of hypoxic, sulfide-laden water have also occurred in some cases (Weeks et al., 2002). Localized, seasonal hypoxic "dead zones" have emerged in economically valuable coastal areas such as the Gulf of Mexico (Turner et al., 2008; Rabalais et al., 2010), the Baltic Sea (Conley et al., 2009), and the 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 O_2 threshold (less than 2 mg l^{-1} or ~60 µmol^{-1}) is found at 300 m depth and upwelling of increasingly hypoxic waters is well documented (Karstensen et al., 2008). Hypoxic waters in the northern Arabian Sea and Bay of Bengal are located close to continental shelf areas. Long-term measurements reveal that O_2 concentrations are declining in these waters, with *medium evidence* that economically significant mesopelagic fish populations are being threatened by a reduction in suitable habitat as respiratory stress increases (Koslow et al., 2011). It should be noted that hypoxia profiles based on a critical threshold of 60 µmol kg^{-1} can convey an overly simplistic message given that critical concentrations of O_2 in this regard are very much species, size, temperature, and life history stage specific. This variability in sensitivity is, however, a critical determinant for any attempt to understand how ecosystems will respond to changing future O_2 levels (Section 6.3.3).

There is *high agreement* among modeling studies that O_2 concentrations will continue to decrease in most parts of the Ocean due to the effect of temperature on O_2 solubility, microbial respiration rates, ocean ventilation, and ocean stratification (Figure 30-9c,d; WGI AR5 Table 6.14; Andrews et al., 2013), with implications for nutrient and carbon cycling, ocean productivity, marine habitats, and ecosystem structure (Section 6.3.5). The outcomes of these global changes are *very likely* to be influenced by regional differences in variables such as wind stress, coastal processes, and the supply of organic matter.

30.4. Global Patterns in the Response of Marine Organisms to Climate Change and Ocean Acidification

Given the close relationship between organisms and ecosystems with the physical and chemical elements of the environment, changes are expected in the distribution and abundance of marine organisms in response to ocean warming and acidification (Section 6.3; Boxes CC-MB, CC-OA). Our understanding of the relationship between ocean warming and acidification reveals that relatively small changes in temperature and other variables can result in often large biological responses that range from simple linear trends to more complex non-linear outcomes. There has been an increase in studies that focus on the influence and consequences of climate change for 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.

Evidence of global and regional responses of marine organisms to recent climate change has been shown through assessments of multiple studies focused on single species, populations, and ecosystems (Tasker, 2008; Thackeray et al., 2010; Przeslawski et al., 2012; Poloczanska et al., 2013). The most comprehensive assessment, in terms of geographic spread and number of observed responses, is that of Poloczanska et al. (2013). This study reveals a coherent pattern in observed responses of ocean life to recent climate change across regions and taxonomic groups, with 81% of responses by organisms and ecosystems being consistent with expected changes to recent climate change (*high confidence*; Box CC-MB). On average, spring events in the Ocean have advanced by 4.4 ± 0.7 days per decade (mean ± SE) and the leading edges of species' distributions have extended (generally poleward) by 72.0 ± 0.35 km per decade. Values were calculated from data series ranging from the 1920s to 2010, although all series included data after 1990. The fastest range shifts generally occurred in regions of high thermal velocity (the speed and direction at which isotherms move (Burrows et al., 2011; Section 30.3.1.1)). Subsequently, Pinsky et al. (2013), using a database of 360 fish and invertebrate species and species groups from coastal waters around North America, showed differences in the speed and directions that species shift can be explained by differences in local climate velocities (Box CC-MB).

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. Although the latter may complicate attribution attempts in many sub-regions, interactions between the two groups of stressors may also represent opportunities to reduce the overall effects on marine organisms and processes of the environmental changes being driven by climate change (including ocean acidification) (Crain et al., 2008; Griffith et al., 2012).

30.5.1. High-Latitude Spring Bloom Systems

High-Latitude Spring Bloom Systems (HLSBSs) stretch from 35°N to the edge of the winter sea ice (and from 35°S to the polar front) and provide 36% of world's fish catch (Figure 30-1b). Although much of the North Pacific is iron limited (Martin and Fitzwater, 1988) and lacks a classical spring bloom (McAllister et al., 1960), strong seasonal variability of primary productivity is pronounced at all high latitudes because of seasonally varying photoperiod and water column stability (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 as well as the spatial and temporal synchrony between successive trophic production peaks (Hjort, 1914; Cushing, 1990; Beaugrand et al., 2003; Beaugrand and Reid, 2003).

30

Frequently Asked Questions

FAQ 30.2 | Does slower warming in the Ocean mean less impact on plants and animals?

The greater thermal inertia of the Ocean means that temperature anomalies and extremes are lower than those seen on land. This does not necessarily mean that impacts of ocean warming are less for the ocean than for land. A large body of evidence reveals that small amounts of warming in the Ocean can have large effects on ocean ecosystems. For example, relatively small increases in sea temperature (as little as 1°C to 2°C) can cause mass coral bleaching and mortality across hundreds of square kilometers of coral reef (*high confidence*). Other analyses have revealed that increased temperatures are spreading rapidly across the world's oceans (measured as the movement of bands of equal water temperature or isotherms). This rate of warming presents challenges to organisms and ecosystems as they try to migrate to cooler regions as the Ocean continues to warm. Rapid environmental change also poses steep challenges to evolutionary processes, especially where relatively long-lived organisms such as corals and fish are concerned (*high confidence*).

30.5.1.1. Observed Changes and Potential Impacts

30.5.1.1.1. North Atlantic

The average temperature of the surface waters of the North Atlantic HLSBS has warmed by 0.07°C per decade, resulting in an increase in sea temperature of 0.44°C between 1950 and 2009 (*likely*) (p-value = 0.15; Table 30-1). Over the same period, both winter and summer temperatures have increased significantly (0.05°C per decade and 0.12°C per decade respectively, p-value ≤ 0.05). Since the 1970s, the Atlantic Ocean has warmed more than any other ocean basin (0.3°C per decade; Figure 30-2a; WGI AR5 Section 3.2.2), 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 (MacKenzie and Schiedek, 2007a,b; Levitus et al., 2009; Lee et al., 2011; González-Taboada and Anadón, 2012). Basin-wide warming in the North Atlantic since the mid-1990s has been driven by global warming and the current warm phase of the Atlantic Multi-decadal Oscillation (AMO) (Wang and Dong, 2010; WGI AR5 Section 14.7.6).

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

Climate change is *virtually certain* to drive major changes to the northern fringes of the Atlantic HLSBS by 2100. For the Barents Sea region, which borders the HLSBS and Arctic regions, modeling projections from 1995 to 2060 (SRES B2 scenario) gave an increase in phytoplankton production of 8%, an increase in Atlantic zooplankton production of 20%, and a decrease of Arctic zooplankton production of 50% (Ellingsen et al., 2008). These changes result in a total increase in zooplankton production in the HLSBS section of the Barents Sea and a decrease in the Arctic section. Together with poleward shifts of fish species, a substantial increase in fish biomass and catch is also *very likely* at the northern fringes of the HLSBS (Cheung et al., 2011). However, for some species such as 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 continuous temperature increase is *very likely* to cause discontinuous changes in conditions. The limited migration potential for this small pelagic fish is also *likely* to drive an eastward shift in spawning areas to new spawning grounds along the Novaja Semlja coast (Huse and Ellingsen, 2008).

Observations of fish and other species moving to higher latitudes (Beare et al., 2005; Perry et al., 2005; Collie et al., 2008; Lucey and Nye, 2010) within the North Atlantic HLSBS are consistent with results of modeling exercises (Stenevik and Sundby, 2007; Cheung et al., 2011). Examples from the Barents (Section 28.2.2.1), Nordic, and North Seas (Box 6-1; Section 23.4.6) show how warming from the early 1980s influenced North Atlantic ecosystems, where substantial biological impacts such as large-scale modification of the phenology, abundance, and distribution of plankton assemblages and reorganization of fish assemblages have been observed (Beaugrand et al., 2002; Edwards, 2004; Edwards and Richardson, 2004; Tasker, 2008; Nye et al., 2009; Head and Pepin, 2010; Simpson et al., 2011). The ranges of some cold-water zooplankton assemblages in the northeast Atlantic have contracted towards the Arctic since 1958, and have been replaced by warm-water zooplankton assemblages (specifically copepods) (*high confidence*), which moved up to 1000 km northward (Beaugrand et al., 2002; Beaugrand, 2009). Although changes to surface circulation may have played a role (Reid et al., 2001), the primary driver of the shift was shown to be regional warming (Beaugrand et al., 2002; Beaugrand, 2004). Reorganization of zooplankton communities and an observed decline in mean size has implications for energy transfer to higher trophic levels including commercial fish stocks (Beaugrand et al., 2003; Kirby and Beaugrand, 2009; Lindley et al., 2010; Section 23.4.6). 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; Genner et al., 2010; Hermant et al., 2010; Lucey and Nye, 2010; Simpson et al., 2011). The diversity of zooplankton and fish has increased as more diverse warm-water assemblages extend northward in response to changing environmental conditions (*high confidence*; Kane, 2007; Hiddink and ter Hofstede, 2008; Beaugrand, 2009; Mountain and Kane, 2010; ter Hofstede et al., 2010; Box 6-1; Section 23.4.6).

The past decade has been the warmest decade ever recorded in the Barents Sea, resulting in large populations of krill shrimp and pelagic and demersal fish stocks linked to the Atlantic and boreal ecosystem of the Barents Sea (*high confidence*; Johannesen et al., 2012; Section 28.2.2.1). Recruitment to boreal fish stocks such as cod, haddock, and herring has increased (Eriksen 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 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 abundance of amphipods of more Arctic origin has decreased, resulting in poorer feeding conditions for polar zooplankton predators such as polar cod (*Boreogadus saida*). Blue whiting (*Micromesistius poutassou*), which spawns west of the British Isles and feeds on zooplankton in the Norwegian Sea during the summer, extended their summer feeding distribution into the Barents Sea during the recent warm period.

The Norwegian Sea is one of the two core regions for the herbivore copepod *Calanus finmarchicus*, an important prey species for pelagic fish and early life stages of all fish around the rim of this high-latitude sea 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 that started in the early 1980s (Huse et al., 2012). The individual size of herring has also increased, enabling longer feeding migrations to utilize boreal zooplankton occurring closer to distant Arctic water masses. Mackerel (*Scomber scombrus*) has advanced northward and westward into Icelandic waters (Astthorsson et al., 2012) and was even observed in East Greenland water in summer 2013 (Nøttestad et al., 2013). Since 2004, the sum of spawning stock biomass of the three pelagic fish species (herring, blue whiting, and mackerel) leveled out at around 16 million tonnes.

Observed changes in the phenology of plankton groups in the North Sea over the past 50 years are driven by climate forcing, in particular regional warming (*high confidence*; Edwards and Richardson, 2004; Wiltshire and Manly, 2004; Wiltshire et al., 2008; Lindley et al., 2010; Lindley and Kirby, 2010; Schluter et al., 2010), although responses are species-specific with substantial variation within functional groups (Edwards and Richardson, 2004; Box 6-1). For example, the peak maximum abundance of the copepod *C. finmarchicus* advanced by 10 days from the 1960s to the 2000s, but its warm-water equivalent, *C. helgolandicus*, did not advance (Bonnet et al., 2005). 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 per decade 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 northward while abundant warm-water species shifted southward, 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., 2004, 2005).

In the northeast Atlantic, range expansions and contractions linked to changing climate have also been observed in benthic crustaceans, bivalves, gastropods, and polychaetes (*medium confidence*; Mieszkowska et al., 2007; Beukema et al., 2009; Berke et al., 2010). For example, the southern range limit of the common intertidal barnacle, *Semibalanus balanoides*, contracted northward along European coastlines at a rate of 15 to 50 km per decade since 1872, and its retreat is attributed to reproductive failure as winter temperatures warm (Southward et al., 2005; Wethey and Woodin, 2008). *Chthamalus montagui*, its warm-water competitor, increased in abundance to occupy the niche vacated by *S. balanoides* (*high confidence*; Southward et al., 1995; Poloczanska et al., 2008).

Many of the longest and most comprehensive time series used to investigate the ecological consequences of climate fluctuations and fishing, that span periods of cooling and warming over the past century, are from the northeast Atlantic (Toresen and Østvedt, 2000; Southward et al., 2005; Sundby and Nakken, 2008; Edwards et al., 2010; Poloczanska et al., 2013). Meta-analysis of 288 long-term data sets (spanning up to 90 years) of zooplankton, benthic invertebrates, fish, and seabirds from the OSPAR Commission Maritime Area in the North-east Atlantic showed widespread changes in distribution, abundance, and seasonality that were consistent (77%) with expectations from enhanced greenhouse warming (Tasker, 2008). The study brought 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 International Council for the Exploration of the Sea (ICES) Working Groups. In particular, observations indicated poleward 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 (*high confidence*).

The major portion of the literature on the influence of climate change on the North Atlantic region covers time spans that are longer than for most other sub-regions of the Ocean. Even here, however, the bulk of the literature is limited to the last 30 to 50 years. The few publications covering the first half of the 20th century represent an important longer term perspective on the influence of climate change (Toresen and Østvedt, 2000; Drinkwater, 2006; Sundby and Nakken, 2008; Bañón, 2009; Astthorsson et al., 2012). For example, distinct changes in fauna were associated with a pronounced warming period over 1920–1940 (Wood and Overland, 2010), when fish and other fauna shifted northward (Iversen, 1934; Southward et al., 2005; Drinkwater, 2006; Hátún et al., 2009). The major lesson from these reports is that a rapid large-scale temperature increase occurred in the high-latitude North Atlantic between the 1920s and 1940s, with basin-scale consequences for marine ecosystems that are comparable to warming and observed impacts over the last 30 years. The former event was of great concern within the scientific community, particularly during the late 1940s and early 1950s (Iversen, 1934; Tåning, 1949, 1953; Southward, 1980). However, with the subsequent long-term cooling in the 1970s, discussion around climate responses was discontinued (Southward, 1980). The centennial-long perspective indicates that multi-decadal variability has played a major role in changes observed over the past 30 years. The 150-year instrumental record shows distinct warm phases of the AMO during approximately 1930–1965 and from 1995, and cool phases between approximately 1900–1930 and 1960–1995 (WGI AR5 Section 14.7.6). However, it is *virtually certain* that the enhanced warming in recent decades cannot be explained without external forcing (WGI AR5 Section 10.3.1.1.3). Understanding the changes in inter-decadal variability over the next century is particularly important. The current warm phase of the AMO is *likely* to terminate in the next few decades, leading to a cooling influence in the North Atlantic and potentially offsetting some of the effects of global warming (WGI AR5 Sections 11.3.2.4.1, 14.7.6). Over the transition period, the climate of the North Atlantic is *likely* to change more rapidly than during previous transitions since 1900.

30.5.1.1.2. North Pacific

Sub-decadal variability in the North Pacific HLSBS is dominated by ENSO (Trenberth, 1990; WGI AR5 Section 14.4). Unlike the North Atlantic HLSBS, the North Pacific HLSBS does not show any significant trends in temperature over time, *very likely* as a consequence of climate variability influences on long-term warming patterns (1950–2009; Table 30-1). Decadal and longer periods of variability in the North Pacific are reflected in the principal mode, the Pacific Decadal Oscillation (PDO; WGI AR5 Section 14.7.3), with periodicities in SST of both 15 to 25 years and 50 to 70 years (Minobe, 1997; Mantua and Hare, 2002). Further modes of climate variability include the North Pacific Gyre Oscillation (NPGO; Di Lorenzo et al., 2008; Chhak et al., 2009). The PDO exhibits SST anomalies of one sign along the eastern boundary and the opposite sign in western and central Pacific. The PDO has been reported to have an anthropogenic component (Bonfils and Santer, 2011) but confidence in this is *very low* (*limited evidence*, *low agreement*; WGI AR5 Section 10.3.3). The interplay of the phases of these modes of variability has strong influence on high-latitude Pacific ecosystems (*very high confidence*). In the space of 3 years, the eastern North Pacific fluctuated from one of the warmest years in the past century (2005) to one of the coldest (2008) (McKinnell et al., 2010; McKinnell and Dagg, 2010). This rapid change was accompanied by large changes in primary productivity, zooplankton communities, and fish and seabird populations (McKinnell et al., 2010; McKinnell and Dagg, 2010; Batten and Walne, 2011; Bi et al., 2011; Keister et al., 2011).

Climate transitions among phases of variability tend to be characterized by abrupt reorganization of the ecosystems as dynamic trophic relationships among species alter (Hunt et al., 2002; Peterson and Schwing, 2003; Litzow and Ciannelli, 2007; Litzow et al., 2008; Alheit, 2009). Periods of broad-scale environmental change were observed across high-latitude ecosystems in the North Pacific HLSBS (eastern Bering Sea and Gulf of Alaska) during 1976–1978, 1987–1989, and 1998–1999. These periods were associated with regime shifts in foraging fish that occurred in 1979–1982, 1988–1992, and 1998–2001. The changes indicate how basin-scale variability such as the PDO can manifest across distinct ecosystems (Overland et al., 2008; Link et al., 2009a,b). Phenological shifts observed in the zooplankton communities of the North Pacific were *very likely* in response to decadal climate variability, with distinct changes noted after the climate shifts of the 1970s and 1990s (Mackas et al., 1998; Peterson and Schwing, 2003; Chiba et al., 2006). Modeling evidence suggests a weak shift in PDO toward more occurrences of the negative phase but the credibility of projections remains uncertain (WGI AR5 Section 14.7.3). It is *about as likely as not* that the PDO will change its form or behavior in the future (WGI AR5 Section 14.7.3).

The Kuroshio-Oyashio Extension (KOE) in the northwest Pacific displays pronounced decadal-scale variability (Yatsu et al., 2008; Sugisaki et al., 2010). "Warm periods" in the mid-1970s and late 1980s were accompanied by dramatic changes in pelagic ecosystems and sardine and anchovy stocks (Chiba et al., 2008; Yatsu et al., 2008). Observations and climate model simulations indicate that global warming is *likely* to further alter the dynamics of the Kuroshio Current and the KOE over the coming century (McPhaden and Zhang, 2002; Sakamoto et al., 2005; Wu et al., 2012; Zhang et al., 2014). Alteration of the KOE will alter the timing, magnitude, and structure of spring blooms in the western Pacific and have implications for pelagic fish recruitment, production, and biogeochemical cycles (Ito et al., 2004; Hashioka et al., 2009; Yatsu et al., 2013).

Commercial catches of salmon species in the North Pacific HLSBS follow decadal fluctuations in climate (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 catch to date, and warming trends are *about as likely as not* to have contributed to recent peaks in some sub-regions (Morita et al., 2006; Irvine and Fukuwaka, 2011). Poleward range shifts of some large pelagic fish in the western North Pacific, such as yellowtail *Seriola quinqueradiata* and Spanish mackerel *Scomberomorus niphonius*, were attributed, in part, to regional warming (*high confidence*) and these two species are projected to shift 39 to 71 km poleward from the 2000s to 2030s under SRES A1B (Tian et al., 2012; Jung et al., 2014). Anticipating ecological responses to future anthropogenic climate change also requires evaluation of the role of changes to climate beyond warming per se. For example, declining sea level pressure in the North Pacific is *likely* influenced by anthropogenic forcing (Gillett et al., 2003; Gillett and Stott, 2009; WGI AR5 Section 10.3.3.4) and sea level pressure 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 northern fringe of the Bering Sea is among the most productive of marine sub-regions and includes the world's largest single-species fishery, walleye pollock (*Theragra chalcogramma*; Hunt et al., 2010). This region underwent major changes in recent decades as a result of climate variability, climate change, and fishing impacts (Litzow et al., 2008; Mueter and Litzow, 2008; Jin et al., 2009; Hunt et al., 2010; Section 28.2.2.1). Seasonal sea ice cover declined since the 1990s (to 2006), although there is no linear trend between 1953 and 2006, and the initiation of spring ice retreat over the southeastern Bering Sea shelf started to occur earlier (Wang et al., 2007a). Concurrent with the retreat 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), 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 sub-Arctic fauna (*high confidence*; Wang et al., 2006a; Mueter and Litzow, 2008).

Over a vast region of the eastern Pacific stretching from southern Chile to the Aleutian Islands, waters low in dissolved O_2 (Oxygen Minimum Zone (OMZ)) are found at 300 m depth (Karstensen et al., 2008). Sporadic upwelling of these low-O_2 waters along the continental shelf is well documented, where biological respiration can further reduce dissolved O_2 levels and result in hypoxic or anoxic conditions that lead to mortality of coastal fishes and invertebrates (Grantham et al., 2004; Chan et al., 2008). The magnitude and severity of seasonal hypoxic conditions in shallow-shelf waters of the eastern North Pacific HLSBS increased in recent decades (Bograd et al., 2008; Chan et al., 2008). In addition, minimum pH values in the water column usually occur near the depths of the OMZ (WGI AR5 Box 3.2). A shoaling of the aragonite saturation horizon has *likely* resulted in low-aragonite conditions within the density layers being upwelled on the shelf of the west coast of the USA, increasing the risk of seasonally upwelled water being relatively acidified (Feely et al., 2008) with observed impacts on Pacific oyster (*Crassostrea gigas*) hatcheries (Barton et al., 2012). In the time period 1991–2006, reductions in pH in the North Pacific between 800 and ~100 m were attributed in approximately equal measure to anthropogenic and natural variations (Byrne et al., 2010; WGI AR5 Section 3.8.2; WGI AR5 Figure 3.19).

30.5.1.1.3. Southern Hemisphere

The seasonal peaks in phytoplankton productivity in the Southern Hemisphere are much less pronounced and are of smaller magnitude than those at Northern Hemisphere high latitudes (Yoder et al., 1993). The Southern Hemisphere HLSBS is broadly bounded by the subtropical front and the sub-Antarctic front. Associated with the subtropical front is intense biological activity of 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*, extended its range south of 60° in the southwest Pacific (141°E to 145°E) over the 2 decades since 1983 (Cubillos et al., 2007). Although the drivers for this range extension are not clear, it was proposed that the extension is facilitated by surface warming or changes in the abundance of grazing zooplankton.

Large regions of the sub-Antarctic surface waters are *likely* to become undersaturated with respect to aragonite during winter by 2030, which will impact calcifying plankton and Southern Ocean ecosystems (McNeil and Matear, 2008; Bednaršek et al., 2012; Section 28.2.2.2). Shell weights of the modern foraminifer, *Globigerina bulloides*, in the sediments of the sub-Antarctic region of the HLSBS south of Australia were observed to be 30 to 35% lower than those from sediment cores representing preindustrial periods, consistent with a recent decline in pH (Moy et al., 2009). Examination of the pteropod, *Limacina helicina antarctica*, captured from polar waters further south shows severe levels of shell dissolution consistent with the shoaling of the aragonite saturation horizon and indicates that the impact of ocean acidification is already occurring (Bednaršek et al., 2012).

While the South Pacific HLSBS has not shown warming overall, both the warmest and coolest months show a slight, but significant, increase over time (both 0.05°C per decade from 1950 to 2009, p-value ≤ 0.05; Table 30-1), although some areas within this sub-region have warmed. For example, the western Tasman Sea has shown enhanced warming since 1900 as compared to average global trends (*high confidence*). This has been driven by changes in large-scale wind-forcing leading to a southward expansion of the South Pacific STG and intensification of the southward-flowing East Australian Current (EAC; Cai, 2006; Hill et al., 2008; Wu et al., 2012; WGI AR5 Section 3.6.2). Model simulations suggest both stratospheric ozone depletion and greenhouse forcing contribute 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 than they were in the mid-20th century (Ling, 2008; Pitt et al., 2010; Last et al., 2011). Warming facilitated the establishment of the grazing urchin, *Centrostephanus rodgersii*, in eastern Tasmania during the late 1970s (*high confidence*), which has resulted in deleterious effects on macroalgal beds (Ling, 2008; Ling et al., 2008, 2009; Banks et al., 2010).

30.5.1.2. Key Risks and Vulnerabilities

Projected changes to the temperature of surface waters match those of the past 50 years, with average sea temperatures in the HLSBS regions projected to increase by 0.35°C to 1.17°C in the near term (2010–2039) and by 1.70°C to 4.84°C over the long term (2010–2099) under the "business as usual" (BAU) RCP8.5 scenario (Table SM30-4). Under the lower case scenario considered here (RCP2.6), projected rates of regional warming are much lower (0.12°C to 0.79°C) in the near term, with slight cooling for some regions in the long term (–0.16°C to 1.46°C). Risks to HLSBS from warming of surface waters include changes to primary production and carbon cycling, and the reorganization of ecosystems in response to warmer and more acidified oceans. Both primary production and the timing of the spring bloom in HLSBS are very sensitive to environmental change. Latitudinal shifts in the distribution of phyto- and zooplankton communities will alter seasonality, community composition, and bloom dynamics (Beaugrand, 2009; Ito et al., 2010; Shoji et al., 2011). Alteration of the structure and composition of plankton communities can propagate through high-latitude food webs due to tight trophic linkages (Edwards and Richardson, 2004; Beaugrand et al., 2010; Beaugrand and Kirby, 2010). Mechanisms are complex, and tend to be non-linear, with impacts on ecosystems, fisheries, and biogeochemical cycles being hard to project with any certainty (Box CC-PP). A reorganization of commercial fish stocks, with attendant social and economic disruption, is a key risk of ongoing climate change in HLSBS sub-regions. AR4 reported that the productivity of some marine fisheries is *likely* to increase in the North Atlantic (WGII AR4 Sections 10.4.1, 12.4.7). A large number of publications since then has substantially extended documentation of these trends and has begun to elucidate the nuances in how marine ecosystems and organisms respond (Sumaila et al., 2011).

30

An additional risk exists for sub-polar areas from the loss of seasonal sea ice. Decreases in seasonal sea ice 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, enhance primary production and attending 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 (Box CC-PP). The decline in Arctic sea ice will open ecological dispersal pathways, as well as new shipping routes (Section 30.6.2.3), 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).

HLSBSs are also vulnerable to rapid changes in the carbonate chemistry of ocean waters. Ocean acidification will produce additional and large-scale challenges. There is *medium agreement* that calcifying organisms in these regions will be negatively affected 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 (Figure 30-1a). Equatorial Upwelling Systems (EUS) produce highly productive "cold tongues" that stretch westward across equatorial areas, which is different from other upwelling systems (e.g., EBUE; Section 30.5.5). The associated upwelling is a consequence of the Earth's rotation and easterly (westward) winds and currents, which drive water northward and southward at the northern and southern edges of these sub-regions. As result, cold, nutrient-rich, and high CO_2/low pH waters are transported from the deeper layers of the Ocean to the surface, driving high levels of primary productivity that support 4.7% of total global fisheries productivity (Table SM30-1; Figure 30-1b). Interannual modes of variability (e.g., ENSO; WGI AR5 Section 14.4) dominate EUS, particularly in the Pacific (Barber et al., 1994; McCarthy et al., 1996; Signorini et al., 1999; Le Borgne et al., 2002;

Christian and Murtugudde, 2003; Mestas-Nuñez and Miller, 2006; Pennington et al., 2006; Wang et al., 2006b). Upwelling of the Pacific EUS declines during El Niño events, when the trade winds weaken, or even reverse, and is strengthened during La Niña events. ENSO periodicity controls primary productivity and consequently has a strong influence over associated fisheries production (Mestas-Nuñez and Miller, 2006). The Intertropical Convergence Zone (ITCZ; WGI AR5 Section 14.3.1.1), an important determinant of regional ocean temperature, is located at the edges of the Indian and Pacific equatorial upwelling zone and influences a range of variables including productivity, fisheries, and precipitation. The EUS are also affected by inter-decadal variability (e.g., Inter-decadal Pacific Oscillation (IPO); Power et al., 1999; WGI AR5 Section 14.3).

30.5.2.1. Observed Changes and Potential Impacts

The average sea temperature associated with the EUS has increased significantly (p-value ≤ 0.05), by 0.43°C and 0.54°C from 1950 to 2009 in the Pacific and Atlantic EUS, respectively (Table 30-1). In the Pacific, regional variability in SST trends is driven by the temporal patterns in ENSO and the more frequent El Niño Modoki or Central Pacific El Niño events in recent decades (*high confidence*; Ashok et al., 2007; Yu and Kao, 2007; Lee and McPhaden, 2010; WGI AR5 Section 14.2.4.4). The faster warming of the Atlantic EUS is *likely* to be associated with a weakening of upwelling (Tokinaga and Xie, 2011). SLR in the eastern equatorial Pacific has been decreasing by up to –10 mm yr^{-1} since 1993 (Church et al., 2006; Figure 30-5).

Coral reefs in the EUS of the eastern Pacific (e.g., Galápagos and Cocos Islands) have relatively low species diversity and poorly developed carbonate reef frameworks, due to the low pH and aragonite saturation of upwelling waters (*high confidence*; Glynn, 2001; Manzello et al., 2008; Manzello, 2010). Prolonged periods of elevated temperature associated with El Niño have negatively affected corals, kelps, and associated organisms, and resulted in several possible local extinctions (*high confidence*; Glynn, 2011). Since 1985, coral reefs from west of South America to the Gilbert Islands of Kiribati have experienced the highest levels of thermal stress relative to other areas (Donner et al., 2010). In 1982/1983, mass coral bleaching and mortality affected most of the reef systems within the eastern equatorial Pacific (Glynn, 1984; Baker et al., 2008). Subsequent canonical El Niño and Central Pacific El Niño events in 1997/1998, 2002/2003, 2004/2005, and 2009/2010 (WGI AR5 Section 14.4.2; WGI AR5 Figure 14.13) triggered mass coral bleaching by adding to the background increases in sea temperatures (*high confidence*; Donner et al., 2010; Obura and Mangubhai, 2011; Vargas-Ángel et al., 2011). In some locations, impacts of El Niño have also interacted with other anthropogenic changes, such as those arising from changes to 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 is *virtually certain* to continue to be a major driver of oceanic variability over the coming century, although not all models can accurately replicate its behavior (WGI AR5 Section 9.5.3). Superposition of a warming ocean on future ENSO activity (possibly modified in frequency and intensity) is *likely* to result in oceanic conditions that are different from those experienced during past El Niño and La Niña events (Power and Smith, 2007). Temperatures within EUS sub-regions are projected to continue to warm significantly (p-value ≤ 0.05). Under RCP8.5, SST of the Atlantic EUS is projected to increase by 0.81°C over 2010–2039 and 2.56°C over 2010–2099, with similar increases projected for the Pacific EUS (Table SM30-4). Differences between RCPs for the two EUS become clear beyond mid-century, with warming of SST over 2010–2099 being 0.43°C and 0.46°C under RCP2.6, and 3.01°C and 3.03°C under RCP8.5, for Pacific and Atlantic EUS respectively (Table SM30-4). These projected increases in sea temperature will increase heat stress and ultimately irreversibly degrade marine ecosystems such as coral reefs (*very likely*). Further increases in atmospheric CO_2 will cause additional decrease in pH and aragonite saturation of surface waters (adding to the low pH and aragonite saturation of upwelling conditions), with significant differences between emission trajectories by the middle of the century. These changes in ocean carbonate chemistry are *very likely* to negatively affect some

Frequently Asked Questions

FAQ 30.3 | How will marine primary productivity change with ocean warming and acidification?

Drifting microscopic plants known as phytoplankton are the dominant marine primary producers at the base of the marine food chain. Their photosynthetic activity is critically important to life in general. It provides oxygen, supports marine food webs, and influences global biogeochemical cycles. 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 (*low confidence*). Changes have been reported to a range of different ocean systems (e.g., High-Latitude Spring Bloom Systems, Subtropical Gyre Systems, Equatorial Upwelling Systems, and Eastern Boundary Upwelling Ecosystems), some of which are consistent with changes in ocean temperature, mixing, and circulation. However, direct attribution of these changes to climate change is made difficult by long-term patterns of variability that influence productivity of different parts of the Ocean (e.g., Pacific Decadal Oscillation). Given the importance of this question for ocean ecosystems and fisheries, longer time series studies for understanding how these systems are changing as a result of climate change are a priority (*high agreement*).

marine calcifiers, although many of the species from this region are adapted to the low aragonite and calcite saturation states that result from equatorial upwelling, albeit with much lower rates of calcification (Manzello, 2010; Friedrich et al., 2012). 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 *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; WGI AR5 Section 12.4.4.2). There is also low agreement between different CMIP5 General Circulation Models (GCMs) on how ocean warming will affect ENSO, with no significant change to ENSO amplitude in half of 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 GCMs (Collins et al., 2010). Other studies have looked at the interaction between the STG and EUS, and 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 consequences for pelagic fisheries resulting from the migration of fish stocks deriving from changing distribution of particular sea temperatures (Lehodey et al., 2006, 2008, 2011; Cheung et al., 2010; Sumaila et al., 2011; Bell et al., 2013b). These projections suggest that fisheries within EUS will experience increased vulnerability as a result of climate change (*low confidence*).

30.5.3. Semi-Enclosed Seas

Semi-Enclosed Seas (SES) represent a subset of ocean sub-regions that are largely land locked and consequently heavily influenced by surrounding landscapes and local climates (Healy and Harada, 1991). In most cases, they support small but regionally significant fisheries (3.3% of global production; Table SM30-1; Figure 30-1b) 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 results in reduced circulation and exchange with ocean waters, and jurisdictions for these water bodies that are shared by two or more neighboring 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 the Red Sea, is the world's warmest sea, with both extreme negative and positive temperature excursions (annual temperature range of 12°C to 35°C). Like other SES, the Arabian Gulf is particularly vulnerable to changing environmental conditions as a result of its landlocked nature. Trends in SST were not significant over the period 1950–2009 (Table 30-1), which is probably due to long-term variability, and a consequence of regional and abrupt changes that occurred in the late 1980s (Conversi et al., 2010). In keeping with this, recent (1985–2002) localized analyses (e.g., Kuwait Bay) show strong and significant warming trends (based in this case on Advanced Very High Resolution Radiometer (AVHRR) National Oceanic and Atmospheric Administration (NOAA) satellite data) of 0.6°C per decade (Al-Rashidi et al., 2009). There is *limited evidence* and *low agreement* as to how this variability influences marine ecosystems and human activities within the Arabian Gulf, although impacts on some ecosystem components (e.g., coral reefs) have been defined to some extent. The mass coral bleaching and mortality that occurred in 1996 and 1998 were a direct result of the sensitivity of reef-building corals to unusually elevated sea temperatures (*high confidence*; Riegl, 2002, 2003; Box CC-CR). These changes to coral reefs have resulted in a loss of fish species that feed on coral-associated invertebrates while herbivores and planktivorous fish abundances have increased (*medium confidence*; Riegl, 2002). Despite coral ecosystems in this sub-region being adapted to some of the highest temperatures in shallow seas 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 limited (Bauman et al., 2010).

30.5.3.1.2. Red Sea

Few studies have focused on attributing recent changes in Red Sea ecosystems to climate change (including ocean acidification). The Red Sea warmed by 0.74°C from 1982 to 2006 (Belkin, 2009), although trends in the average SST, however, are not significant from 1950 to 2009 (p-value > 0.05; Table 30-1) owing to a high degree of variability involved when longer periods were examined (supplementary material in Belkin, 2009). The temperature of the warmest month of the year, however, showed a significant increase over the 60-year period (0.05°C per decade; Table 30-1). 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 (1.46°C, relative to 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 shows that average colony size of corals has declined (*high confidence*) and species' latitudinal limits may have changed (*medium confidence*). The decline in average colony size is ascribed to heat-mediated bleaching as well as increases in coral diseases and crown of thorns starfish (*Acanthaster* sp.) predation (Riegl et al., 2012). The patterns of this decline correlate well with the pattern of recent 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* due to warming temperatures (*medium confidence*; p-value ≥ 0.05; Cantin et al., 2010).

Cantin et al. (2010) proposed that the massive coral *Diploastrea helipora* will cease to grow in the central Red Sea by 2070 under SRES A1B and A2 (*medium confidence*), although this may not hold for other coral species. For example, an increase in linear extension of *Porites* corals, beginning in the 1980s, was recorded in the northern Red Sea (Heiss, 1996), where temperatures have increased by 0.74ºC from 1982 to 2006 (Belkin, 2009), suggesting that these corals were living in sub-optimal conditions (cooler waters). They may therefore benefit from elevated temperature before reaching their thermal threshold, at which point growth rates would be predicted to decline, as they are doing in other 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 (*limited evidence*). Silverman et al. (2007) quantified the sensitivity of net coral reef ecosystem calcification to changes in carbonate chemistry (pH, aragonite saturation). Their results demonstrate a strong negative effect of ocean acidification on ecosystem-scale calcification and decalcification, and show 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, 2009).

30.5.3.1.3. Black Sea

The temperature of the surface waters of the Black Sea increased by 0.96ºC from 1982 to 2006 (Belkin, 2009), which is consistent with other studies (*high confidence*; Buongiorno Nardelli et al., 2010; Bozkurt and Sen, 2011). As with other SES (i.e., Arabian Gulf and Baltic, Mediterranean, and Red Seas), longer data sets do not reveal a significant trend due to large-scale variability prior to 1982, which may be due to the influence of AMO, NAO, and other long-term sources of variability (Table 30-1; supplementary material in 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. As with the Mediterranean and Red Seas, however, a significant upward trend in the temperature is recorded in the warmest month of the year over the period 1950–2009 (Table 30-1). Freshwater discharge from rivers draining into the Black Sea has remained more or less constant since the early 1960s (Ludwig et al., 2009). Increasing water temperature has steadily eliminated the Cold Intermediate Layer (CIL; temperatures below 8°C) throughout the Black Sea basin over 1991–2003 (*high confidence*; Oguz et al., 2003). Reduced water column mixing and upwelling during warmer winter periods has reduced the supply of nutrients to the upper layers of the Black Sea (Oguz et al., 2003) and expanded areas of low O_2 in the deeper parts of the Black Sea, which is the world's largest anoxic marine basin (*high confidence*; Murray et al., 1989). These changes coincided with the collapse of fish stocks and the invasion by the ctenophore, *Mnemiopsis leidyi*, in the 1980s (Oguz et al., 2008), while inputs of nutrients such as phosphate from the Danube River has decreased strongly since 1992–1993 (Oguz and Velikova, 2010). Environmental perturbations explain the declining levels of primary productivity, phytoplankton, bacterioplankton, and fish stocks in the Black Sea from the mid-1990s (Yunev et al., 2007; Oguz and Velikova, 2010). 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 increased substantially since the early 1980s (Aleksandrov et al., 2009; Belkin, 2009), with increases of 1.35°C (1982–2006) being among the highest rate of change seen in any SES (Belkin, 2009). Increases of this magnitude are not seen in longer records throughout the Baltic Sea (1861–2001: MacKenzie et al., 2007; MacKenzie and Schiedek, 2007a,b; 1900–1998: Madsen and Højerslev, 2009). The salinity of the surface and near bottom waters of the Baltic Sea, for example, Gdansk Basin (Aleksandrov et al., 2009) and central Baltic (Fonselius and Valderrama, 2003; Möllmann et al., 2003), decreased from 1975 to 2000, due to changing rainfall and river runoff, and a reduction in the pulses of seawater (vital for oxygenation and related chemical changes) from the North Sea through its opening via the Kattegat (*high confidence*; Samuelsson, 1996; Conley et al., 2009; Hänninen and Vuorinen, 2011). There is a strong vertical zonation within the Baltic Sea in terms of the availability of O_2. The shallow sub-regions of the Baltic are relatively well oxygenated. However, O_2 levels are low in the deeper basins, producing conditions in which 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 1979 (Henriksen, 2009), reputedly due to changing nitrogen loads in the Danish Straits (*medium confidence*) in addition to increasing sea temperature (*very likely*; Madsen and Højerslev, 2009). Reduced phytoplankton production may have decreased the productivity of fisheries in the western Baltic Sea and the Transition Zone (*low* to *medium confidence*; Chassot et al., 2007). Decreasing salinity in the Baltic deep basins may also affect zooplankton reproduction, especially that of the copepod *Pseudocalanus acuspes*, contributing to density-dependent decrease in growth of the commercially important herring and sprat stocks (*high confidence*; Möllmann et al., 2003, 2005; Casini et al., 2011). 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 will occur as sea temperatures increase and the hydrological cycle in the Baltic region changes (*high confidence*; MacKenzie et al., 2012). A combination of climate change-induced oceanographic changes (i.e., decreased salinity and increased temperatures), eutrophication, and overfishing have resulted in major changes in trophic structure in the deep basins of the Baltic Sea (Möllmann et al., 2009). This had important implications for cod, a commercially important top predator (*medium confidence*; Lindegren et al., 2010).

30.5.3.1.5. Mediterranean Sea

The Mediterranean Sea is strongly linked to the climates of North Africa and Central Europe. SST within the Mediterranean increased by 0.43°C from 1957 to 2008 (supplementary material in Belkin, 2009), although analysis of data from 1950 to 2009 detected only a significant trend in summer temperature (0.11°C per decade, p-value ≤ 0.05; Table 30-1) due to large fluctuations in SST prior to the 1980s. Surface temperatures increased in the Mediterranean Sea consistent with significant increases in SST at a number of monitoring sites (*robust evidence*, *high agreement*; e.g., Coma et al., 2009; Conversi et al., 2010; Calvo et al., 2011). It is *likely* that temperatures, along with salinity, have also increased at depth (400 m or more) in the western Mediterranean Sea over the past 30 to 40 years which, when analyzed in the context of heat budget and water flux of the Mediterranean, is consistent with anthropogenic greenhouse warming (Bethoux et al., 1990; Rixen et al., 2005; Vargas-Yáñez et al., 2010). Large-scale variability such as the AMO and NAO can obscure or accentuate the overall warming trend (Marullo et al., 2011; WGI AR5 Sections 14.5.1, 14.7.6). Relatively warm episodes in the 1870s, 1930–1970s, and since the mid-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 a deepening thermocline, are associated with positive phases of the NAO index (Molinero et al., 2005; Lejeusne et al., 2010).

Sea levels have increased rapidly in some areas over recent decades and are also strongly influenced by NAO phases. The rate has been approximately 3.4 mm yr^{-1} (1990–2009) in the northwest Mediterranean (*high confidence*; Calvo et al., 2011). These influences are reduced when measurements are pooled over longer time scales, resulting in a lower rate of SLR (Massuti et al., 2008). If the positive phase of the NAO is more frequent in the future (Terray et al., 2004; Kuzmina et al., 2005; WGI AR5 Section 14.4.2), then future SLR may be slightly suppressed as a result of atmospheric influences (*medium confidence*; Jordà et al., 2012). As temperatures have increased, the Mediterranean has become more saline (+0.035 to 0.040 psu from 1950 to 2000; Rixen et al., 2005) with the length of the thermal stratification period persisting twice as long in 2006 as 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 SST when examined from 1950 to 2009 (Table 30-1). 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-causing organisms (*likely*; Danovaro et al., 2009). Increasing temperatures are also driving the northward spread of warm-water species (*medium confidence*) such as the sardine *Sardinella aurita* (Sabatés et al., 2006; Tsikliras, 2008), and have contributed to the spread of the invading Atlantic coral *Oculina patagonia* (Serrano et al., 2013). The recent spread of warm-water species that have invaded through the Straits of Gibraltar and the Suez Canal into cooler northern areas is leading to the "tropicalization" of Mediterranean fauna (*high confidence*; Bianchi, 2007; Ben Rais Lasram and Mouillot, 2008; CIESM, 2008; Galil, 2008, 2011). Warming since the end of the 1990s has accelerated the spread of tropical invasive species from the eastern Mediterranean basin (Raitsos et al., 2010; Section 23.6.5).

In addition to general warming patterns, periods of extreme temperatures have had large-scale and negative consequences for Mediterranean marine ecosystems. Unprecedented mass mortality events, which affected at least 25 prominent invertebrate species, occurred during the summers of 1999, 2003, and 2006 across hundreds of kilometers of coastline in the northwest Mediterranean Sea (*very high confidence*; Cerrano et al., 2000; Garrabou et al., 2009; Calvo et al., 2011; Crisci et al., 2011). Events coincided with either short periods (2 to 5 days: 2003, 2006) of high sea temperatures (27°C) or longer periods (30 to 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 these events (e.g., gorgonian coral mortality; Coma et al., 2009), shoot mortality, and anomalous flowering of seagrasses (*high confidence*; Diaz-Almela et al., 2007; Marbà and Duarte, 2010). The frequency and intensity of these types of heat stress events are expected to increase as sea temperatures increase (*high confidence*).

Longer-term data series (over several decades) of changes in relative acidity of the Mediterranean Sea are scarce (Calvo et al., 2011; The MerMex Group, 2011). Recent re-analysis, however, has concluded that the pH of Mediterranean waters has decreased by 0.05 to 0.14 pH units since the preindustrial period (*medium confidence*; Luchetta et al., 2010; Touratier and Goyet, 2011). Anthropogenic CO_2 has penetrated the entire Mediterranean water column, with the western basin being more contaminated than the eastern basin (Touratier and Goyet, 2011). Studies that have explored the consequences of ocean acidification for the biology and ecology of the Mediterranean Sea are rare (Martin and Gattuso, 2009; Rodolfo-Metalpa et al., 2010; Movilla et al., 2012), although insights have been gained by studying natural CO_2 seeps at Mediterranean sites such as Ischia in Italy, where biodiversity decreases with decreasing pH toward the vents, with a notable decline in calcifiers (Hall-Spencer et al., 2008). Transplants of corals, molluscs, and bryozoans along the acidification gradients around seeps reveal a low level of vulnerability to CO_2 levels expected over the next 100 years (*low confidence*; Rodolfo-Metalpa et al., 2010, 2011). However, periods of high temperature can increase vulnerability to ocean acidification, thereby increasing the long-term risk posed to Mediterranean organisms and ecosystems as temperatures warm. Significantly, some organisms such as seagrasses and some macroalgae appeared to benefit from local ocean acidification (Hall-Spencer et al., 2008).

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 will respond faster than most other parts of the Ocean (*high confidence*). Risks to ecosystems within SES are *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 influences such as over-exploitation, pollution, and enhanced runoff 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 (*medium confidence*). A major risk exists for SES from projected increases in the frequency of temperature extremes that drive mass mortality events, increasing water column stabilization leading to reduced mixing, and 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.

Sea temperatures are *very likely* to increase in the five SES under moderate (RCP6.0) to high (RCP8.5) future scenarios. Under BAU (RCP8.5; Table SM30-3), sea temperatures in the SES are projected to increase by 0.93°C to 1.24°C over 2010–2039 (Table SM30-4). Increases of 3.45°C to 4.37°C are projected over 2010–2099, with the greatest increases projected for the surface waters of the Baltic Sea (4.37°C) and Arabian Gulf (4.26°C), and lower yet substantial amounts of warming in the Red Sea (3.45°C) (Table SM30-4). The heat content added to these small ocean regions is *very likely* to increase stratification, 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* increase hypoxia and expand the number and extent of "dead zones." Changing rainfall intensity (Section 23.3; WGI AR5 Section 12.4.5) can exert a strong influence on the physical and chemical conditions within SES, and in some cases will combine with other climatic changes to transform these areas. These changes are likely to increase the risk of reduced bottom-water O_2 levels to Baltic and Black Sea ecosystems (due to reduced solubility, increased stratification, and microbial respiration), which is *very likely* to affect fisheries. These changes will increase the frequency and intensity of impacts arising from heat stress, based on responses to temperature extremes seen over the past 30 years, such as the mass mortality of benthic organisms that occurred in the Mediterranean Sea during the summers of 1999, 2003, and 2006, and the Arabian Gulf in 1996 and 1998. Extreme temperature events such as heat waves are projected to increase (*high confidence*; Section 23.2; IPCC, 2012). Projections similar to those outlined in Section 30.5.4.2 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 (*very high confidence*; Figure 30-10).

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 SM30-1; Figure 30-1b). The CBS include the marginal seas of the northwest Pacific, Indian, and Atlantic Oceans, encompassing the Bohai/Yellow Sea, East China Sea, South China Sea, and Southeast Asian Seas (e.g., the Timor, Arafura, and Sulu Seas, and the northern coast of Australia) in the Pacific; the Arabian Sea, Somali Current system, East Africa coast, Mozambique Channel, and Madagascar in the Indian Ocean; and the Caribbean Sea and Gulf of Mexico in the Atlantic Ocean). Some CBS are dominated by powerful currents such as the Kuroshio (Pacific), or are strongly influenced by monsoons (e.g., Asian-Australian and African monsoons).

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 widespread degradation of CBS ecosystems (Burke et al., 2002, 2011). These influences have combined with steadily increasing ocean temperature and acidification 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, the CBS warmed by 0.14°C to 0.80°C from 1950 to 2009 (Table 30-1), although changes within the Gulf of Mexico/Caribbean Sea sub-region were not significant (p-value > 0.05) over this period. Key sub-regions within the CBS such as the Coral Triangle and Western Indian Ocean warmed by 0.79°C and 0.60°C, respectively, from 1950 to 2009 (Table 30-1). Rates of SLR vary from decreasing sea levels (–5 to –10 mm yr^{-1}) to low (2 to 3 mm yr^{-1}, Caribbean) to very high (10 mm yr^{-1}, Southeast Asia; Figure 30-5) rates of increase. Ocean acidification also varies from region to region (Figure SM30-2), and is influenced by oceanographic and coastal processes, which often have a large human component.

30.5.4.1.1. Bohai/Yellow Sea/East China Sea

The Bohai Sea, Yellow Sea, and the East China Sea (ECS) are shallow marginal seas along the edge of the northwest Pacific that are strongly influenced by the Kuroshio Current (Matsuno et al., 2009), the East Asian Monsoon (EAM), and major rivers such as the Yellow (Huang He) and Yangtze (Changjiang) Rivers. Upwelling of the Kuroshio sub-surface waters provides abundant nutrients that support high levels of primary productivity (Wong et al., 2000, 2001). The ecosystems of the ECS are heavily affected by human activities (e.g., overfishing and pollution), which tend to compound the influence and consequences of climate change.

SST within the ECS has increased rapidly since the early 1980s (*high confidence*; Lin et al., 2005; Jung, 2008; Cai et al., 2011; Tian et al., 2012). The largest increases in SST have occurred in the ECS in winter (1.96°C, 1955–2005) and in the Yellow Sea in summer (1.10°C, 1971–2006; Cai et al., 2011). These changes in SST are closely linked to a weakening of the EAM (e.g., Cai et al., 2006, 2011; Tang et al., 2009) and increasing warmth of the Kuroshio Current (Qi et al., 2010; Zhang et al., 2011; Wu et al., 2012). At the same time, dissolved O_2 has decreased (Lin et al., 2005; Jung, 2008; Qi et al., 2010), with an associated increase in the extent of the hypoxic areas in coastal areas of the Yellow Sea/ECS (Jung, 2008; Tang, 2009; Ning et al., 2011).

Primary productivity, biomass yields, and fish capture rates have experienced large changes within the ECS over the past decades (*limited evidence*, *medium agreement*; *low confidence*; Tang et al., 2003; Lin et al., 2005; Tang, 2009). Fluctuations in herring abundance appear to closely track SST shifts within the Yellow Sea (Tang, 2009). For plankton and fish species, the proportions of warm-water species relative to warm-temperate species in the Changjiang River Estuary (extending to the southern Taiwan Strait) have changed over past decades (Zhang et al., 2005; Ma et al., 2009; Lin and Yang, 2011). Northward shifts in catch distribution for some pelagic fish species in Korean waters were driven, in part, by warming SST (*medium confidence*; Jung et al., 2014). The frequency of harmful algal blooms and blooms of the giant jellyfish *Nemopilema nomurai* in the offshore area of the ECS have increased and have been associated with ocean warming and other factors such as eutrophication (Ye and Huang, 2003; Tang, 2009; Cai and Tan, 2010). Although 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 SST increases.

30.5.4.1.2. South China Sea

The South China Sea (SCS) is surrounded by continental areas and includes large numbers 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 seagrass beds.

The surface waters of the SCS have been warming steadily from 1945 to 1999 with the annual mean SST in the central SCS increasing by 0.92°C (1950–2006; Cai et al., 2009), a rate similar to that observed for the entire Indo-Pacific/Southeast Asian CBS from 1950 to 2009 (0.80°C; Table 30-1). 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 heterogeneous in space and time (Li et al., 2002; Cheng and Qi, 2007; Liu et al., 2007).

Identifying the extent to which climate change is influencing the SCS is difficult due to confounding non-climate change factors and their interactions (e.g., local human pollution, over-exploitation together with "natural" climate variability such as EAM, ENSO, and PDO). Changing sea temperatures have influenced the abundance of phytoplankton, benthic biomass, cephalopod fisheries, and the size of demersal trawl catches in the northern SCS observed over the period 1976–2004 (*limited evidence*, *medium agreement*; Ning et al., 2009). Coral reefs and mangroves are degrading rapidly as a result of both climate change and non-climate change-related factors (*very likely*; Box CC-CR; Chen et al., 2009; China-SNAP, 2011; Zhao et al., 2012). Mass coral bleaching and mortality of coral reefs within the SCS were triggered by elevated temperatures in 1998 and 2007 (Yu et al., 2006; Li et al., 2011). Conversely, warming enabled the establishment of a high-latitude, non-carbonate, coral community in Daya Bay in northern SCS, although this community has recently degraded as a result of increasing anthropogenic stresses (Chen et al., 2009; Qiu et al., 2010).

30.5.4.1.3. Southeast Asian Seas

The Southeast Asian Seas (SAS) include an archipelago of diverse islands that interact with the westward flow of the North Equatorial Current and the Indonesian Throughflow (Figure 30-1a). A large part of this region is referred to as the "Coral Triangle" (Veron et al., 2009). The world's most biologically diverse marine area, it includes parts of Malaysia, Indonesia, the Philippines, Timor Leste, the Solomon Islands, and Papua New Guinea. SST increased significantly from 1985 to 2006 (Peñaflor et al., 2009; McLeod et al., 2010), although with considerable spatial variation. Trends examined over longer periods (1950–2009) show significant warming (+0.80°C, p-value ≤ 0.05; Table 30-1). The sea level is rising by up to 10 mm yr^{-1} in much of this region (Church et al., 2004, 2006; Green et al., 2010). Like other tropical areas in the world, coral reefs within SAS have experienced periods of elevated temperature, which has driven several mass coral bleaching and mortality events since the early 1980s (*high confidence*; Hoegh-Guldberg et al., 2009; McLeod et al., 2010; Figure 30-10a). The most recent occurred during warm conditions in 2010 (Krishnan et al., 2011). 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; WGI AR5 Section 10.4.1). Although calcification rates of some key organisms (e.g., reef-building corals; Tanzil et al., 2009) have slowed over the past 2 decades, it is not possible to conclude that the changes are due to ocean acidification. While a large part of the decline in coral reefs has been due to increasing local stresses (principally destructive fishing, declining water quality, and over-exploitation of key reef species), projected increases in SST represent a major challenge for these valuable ecosystems (*high agreement*; Burke et al., 2002; Burke and Maidens, 2004).

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. SST increased by 0.18°C and 0.26°C in the Arabian Sea and Somali Current, respectively, from 1982 to 2006 (HadSST2; Rayner et al., 2003; Belkin, 2009), which is consistent with the overall warming of the Western Indian Ocean portion of the CBS from 1950 to 2009 (0.60°C; Table 30-1). Salinity of surface waters in the Arabian Sea increased by 0.5 to 1.0% over the past 60 years (Figure 30-6c), due to increased evaporation from warming seas and contributions from the outflows of the saline Red Sea and Arabian Gulf. As in other tropical sub-regions, increasing sea temperatures have increased the frequency of mass coral bleaching and mortality within this region (Wilkinson and Hodgson, 1999; Goreau et al., 2000; Wilkinson, 2004).

The aragonite saturation horizon in both the Arabian Sea and Bay of Bengal is now 100 to 200 m shallower than in preindustrial times as a result of ocean acidification (*medium confidence*; Feely et al., 2004). Shoaling of the aragonite saturation horizon is *likely* to affect a range of organisms and processes, such as the depth distribution of pteropods (zooplankton) in the western Arabian Sea (*medium confidence*; Hitchcock et al., 2002; Mohan et al., 2006). More than 50% of the area of OMZs in the world's oceans occur in the Arabian Sea and Bay of Bengal and long-term measurements reveal that O_2 concentrations are declining in this region (*high confidence*; Helly and Levin, 2004; Karstensen et al., 2008; Stramma et al., 2010; Section 30.3.2.3). The information regarding the consequences 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

The Western Indian Ocean strongly influences the coastal conditions associated with Kenya, Mozambique, Tanzania, Madagascar, La Réunion, Mayotte, and three archipelagos (Comoros, Mauritius, and the Seychelles). Sea temperatures in the Western Indian Ocean have increased by 0.60°C over 1950–2009 (*high confidence*; p-value ≤ 0.05; Table 30-1), increasing the frequency of positive thermal anomalies that have triggered mass coral bleaching and mortality events across the region over the past 2 decades (*high confidence*; Baker et al., 2008; Nakamura et al., 2011; Box CC-HS). Trends in changes in SST and surface salinity vary with location along the East African coastline, with faster rates at higher latitudes (Figure 30-2). Periods of heat stress over the past 20 years have triggered mass coral bleaching and mortality on coral reef ecosystems within this region (McClanahan et al., 2007, 2009a,b,c; Ateweberhan and McClanahan, 2010; Ateweberhan et al., 2011). Steadily increasing sea temperatures have also produced anomalous growth rates in long-lived corals such as *Porites* (*high confidence*; 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-value ≤ 0.05; McClanahan et al., 2007) and benthic fish communities (*high confidence*; p-value ≤ 0.05; Graham et al., 2008; Pratchett et al., 2011a). These changes are *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 populations (p-value ≤ 0.05; Graham et al., 2007). Some of these potential changes can be adverted or reduced by interventions such as the establishment of marine protected areas and changes to fishing management (McClanahan et al., 2008; Cinner et al., 2009; Jury et al., 2010; MacNeil et al., 2010).

30.5.4.1.6. Gulf of Mexico and Caribbean Sea

The Gulf of Mexico and Caribbean Sea 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 almost 75 million people who live in coastal areas of the USA, Mexico, and a range of other Caribbean nations (Adams et al., 2004). The Gulf of Mexico and Caribbean Sea have warmed by 0.31°C and 0.50°C, respectively, from 1982 to 2006 (*very likely*; Belkin, 2009). Warming trends are not significant from 1950 to 2009 (Table 30-1), which may be partly due to spatial variability in warming patterns (Section 30.5.3.1). The Caribbean region has experienced a sustained decrease in aragonite saturation state from 1996 to 2006 (*very likely*; Gledhill et al., 2008). Sea levels within the Gulf of Mexico and Caribbean Sea have increased at the rate of 2 to 3 mm yr^{-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 the confounding influence of growing human populations and activities. The recent expansion of the seasonal hypoxic zone, and the associated "dead zone," in the Gulf of Mexico has been attributed to nitrogen inputs driven by land management (Turner and Rabalais, 1994; Donner et al., 2004) and changes to river flows, wind patterns, and thermal stratification of Gulf waters (*high confidence*; Justić et al., 1996, 2007; Levin et al., 2009; Rabalais et al., 2009). The increases in coastal pollution and fishing have potentially interacted with climate change to exacerbate impacts on marine ecosystems within this region (Sections 5.3.4, 29.3). These changes have often been abrupt and non-linear (Taylor et al., 2012).

A combination of local and global disturbances has driven a large-scale loss of reef-building corals across the Caribbean Sea since the late 1970s (*high confidence*; Hughes, 1994; Gardner et al., 2003). 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 square kilometers in the eastern Caribbean Sea (*high confidence*; Donner et al., 2007; Eakin et al., 2010). Although conditions in 2010 were milder than in 2005, elevated temperatures still occurred in some parts of the Caribbean (Smith et al., 2013). Increasing temperatures in the Caribbean have also been implicated in the spread of marine diseases (Harvell et al., 1999, 2002, 2004) and some introduced species (*likely*; 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 accordingly (Muhling et al., 2011). Fish and invertebrate assemblages in the Gulf of Mexico have shifted deeper in response to SST warming over 1970s–2011 (*medium confidence*; Pinsky et al., 2013).

Coral ecosystems in the Caribbean Sea are at risk from ocean acidification (*very likely*; Albright et al., 2010; Albright and Langdon, 2011), although impacts have yet to be observed under field conditions. Ocean acidification may also be altering patterns of fish recruitment to coral reefs, although direct evidence for how this has affected Caribbean species is lacking (*low confidence*; Dixson et al., 2008, 2010; Munday et al., 2009).

30.5.4.2. Key Risks and Vulnerabilities

Worldwide, 850 million people live within 100 km of tropical coastal ecosystems such as coral reefs and mangroves deriving multiple benefits including food, coastal protection, cultural services, and income from industries such as fishing and tourism (Burke et al., 2011). Marine ecosystems within the CBS are sensitive to increasing sea temperatures (Figure 30-10), although detection and attribution are complicated by the significant influence and interaction with non-climate change stressors (water quality, over-exploitation of fisheries, coastal degradation; Box CC-CR). Warming is likely to have changed the primary productivity of ocean waters, placing valuable ecosystems and fisheries within the ECS at risk (*low* to *medium confidence*). Other risks include the expansion of hypoxic conditions and associated dead zones in many parts of the CBS. Given the consequences for coastal ecosystems and fisheries, these changes are *very likely* to increase the vulnerability of coastal communities throughout the CBS.

Sea temperatures are increasing within many parts of CBS ecosystems (1950–2009; Table 30-1), and will continue to do so over the next few decades and century. Sea temperatures are projected to change by

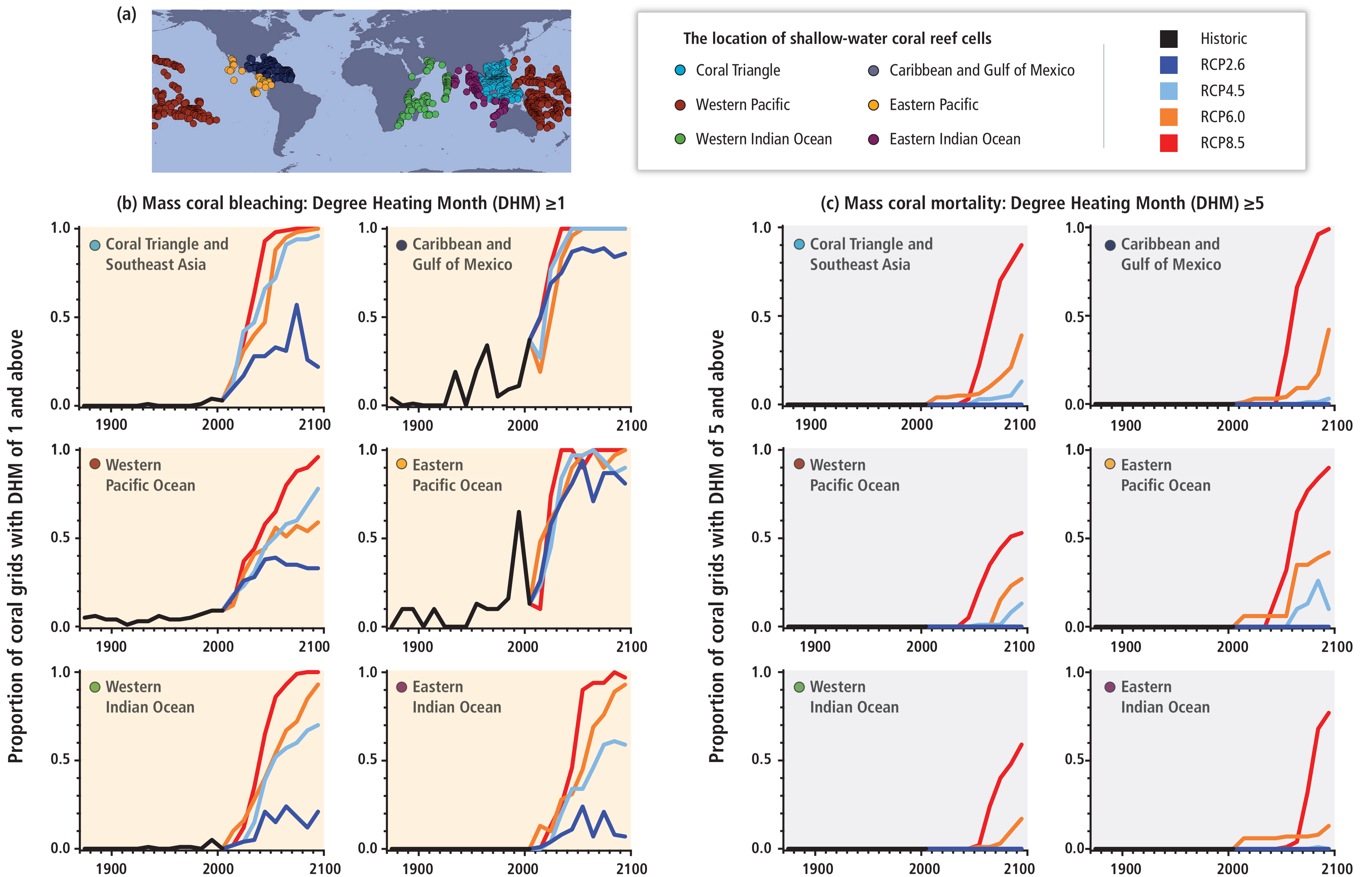


Figure 30-10 | Annual maximum proportions of reef pixels with Degree Heating Months (DHM, Donner et al., 2007) for each of the six coral regions (a, Figure 30-4b)—(b) DHM ≥1 (used for projecting the incidence of coral bleaching; Strong et al., 1997, 2011) and (c) DHM ≥5 (associated with bleaching followed by significant mortality; Eakin et al., 2010)—for the period 1870–2009 using the Hadley Centre Interpolated sea surface temperature 1.1 (HadISST1.1) data set. The black line on each graph is the maximum annual area value for each decade over the period 1870–2009. This value is continued through 2010–2099 using Coupled Model Intercomparison Project Phase 5 (CMIP5) data and splits into the four Representative Concentration Pathways (RCP2.6, 4.5, 6.0, and 8.5). DHM were produced for each of the four RCPs using the ensembles of CMIP models. From these global maps of DHM, 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 sea surface temperature anomalies were derived using a 1985–2000 maximum monthly mean climatology derived in the calculations for Figure 30-4. This was done separately for HadISST1.1, the CMIP5 models, and each of the four RCPs, at each grid cell for every region. DHMs were then derived by adding up the monthly anomalies using a 4-month rolling sum. Figure SM30-3 presents past and future sea temperatures for the six major coral reef provinces under historic, un-forced, RCP4.5 and RCP8.5 scenarios.

0.34°C to 0.50°C over the near term (2010–2039) and by 0.23°C to 0.74°C over the long term (2010–2099) under the lowest RCP scenario (RCP2.6). Under BAU (RCP8.5), CBS sea temperatures are projected to increase by 0.62°C to 0.85°C over the near term and 2.44°C to 3.32°C over the long term (Table SM30-4). Given the large-scale impacts (e.g., mass coral bleaching and mortality events) that have occurred in response to much smaller changes in the past over CBS regions (0.14°C to 0.80°C from 1950–2009; Table 30-1), the projected changes of 2.44°C to 3.32°C over 2010–2099 are *very likely* to have large-scale and negative consequences for the structure and function of many CBS ecosystems (*virtually certain*), especially given the observed sensitivity of coral reefs to relatively small increases in temperature over the past 3 decades (Hoegh-Guldberg, 1999; Eakin et al., 2010; Lough, 2012).

It is *very likely* that coral-dominated reef ecosystems within the CBS (and elsewhere) will continue to decline and will consequently provide significantly less ecosystem goods and services for coastal communities if sea temperatures increase by more than 1°C above current temperatures (Box CC-CR; Figure 30-10). Combining the known sensitivity of coral reefs within the Caribbean and Coral Triangle sub-regions (Strong et al., 1997, 2011; Hoegh-Guldberg, 1999), 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 (DHM ≥ 1) that cause coral bleaching every 1 to 2 years by the mid- to late part of this century (*robust evidence*, *high agreement*; *very high confidence*; Figures 30-4b,c, 30-10, 30-12, SM30-3; van Hooidonk et al., 2013). The frequency of mass mortality events (DHM ≥ 5; Figure 30-10a,b,c) also increases toward a situation whereevents that occur every 1 to 2 years by the mid- to late part of this century under low to high climate change scenarios (*robust evidence*, *high agreement*; *very high confidence*; Hoegh-Guldberg, 1999; Donner et al., 2005; Frieler et al., 2012). Mass mortality events that affect coral reefs will result in changes to community composition in the near term (2010–2039; Berumen and Pratchett, 2006; Adjeroud et al., 2009) and a continuing downward trend in coral cover in the longer term (Gardner et al., 2003; Bruno and Selig, 2007; Baker et al., 2008).

It is *virtually certain* that composition of coral reef fish populations (Graham et al., 2007; Pratchett et al., 2008, 2011a,b) will change. The productivity of many fisheries will decrease (*limited evidence*, *medium agreement*) as waters warm, acidify, and stratify, and as crucial habitat, such as coral reefs, degrade (*low confidence*). 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 goods and services provided by ecosystems such as coral reefs (Hoegh-Guldberg et al., 2009; McLeod et al., 2010).

30.5.5. Eastern Boundary Upwelling Ecosystems

The Eastern Boundary Upwelling Ecosystems (EBUE) include the California, Peru/Humboldt, Canary/northwest Africa, and Benguela Currents. They are highly productive sub-regions with rates of primary productivity that may exceed 1000 g C m^{-2} yr^{-1}. Although these provinces comprise less than 2% of the Ocean area, they contribute nearly 7% of marine primary production (Figure 30-1b) and more than 20% of the world's marine capture fisheries (Pauly and Christensen, 1995). Catches in the EBUE are dominated by planktivorous sardine, anchovy, and horse/jack mackerel, and piscivorous benthic fish such as hake. Nutrient input from upwelling of cooler waters stimulates primary production that is transferred to mid and upper trophic levels, resulting in substantial fish, seabird, and marine mammal populations. As a result, the EBUE are considered "hotspots" of productivity and biodiversity (Block et al., 2011). The high level of productivity is a result of large-scale atmospheric pressure gradients and wind systems that advect surface waters offshore, leading to the upwelling of cold, nutrient-rich waters from depth (Box CC-UP; Chavez and Messie, 2009; Chavez et al., 2011). Upwelling waters are typically low in pH and high in CO_2, and are likely to continue to enhance changes in pH and CO_2 resulting from rising atmospheric CO_2 (Feely et al., 2008; Gruber, 2011).

30.5.5.1. Observed Changes and Potential Impacts

There are extensive studies of the coupled climate-ecosystem dynamics of individual EBUE (e.g., California Current). Decadal variability poses challenges to the detection and attribution of changes within the EBUE to anthropogenic 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, EBUE are projected to warm under climate change, with increased stratification and intensified winds as westerly winds shift poleward (*likely*). However, cooling has also been predicted for some EBUE, resulting from the intensification of wind-driven upwelling (Bakun, 1990). The California and Canary Currents have warmed by 0.73°C and 0.53°C (*very likely*; *p*-value ≤ 0.05, 1950–2009; Table 30-1), respectively, while no significant trend was detected in the sea surface temperatures of the Benguela (*p*-value = 0.44) and Humboldt Currents (*p*-value = 0.21) from 1950 to 2009 (Table 30-1). These trends match shorter-term trends for various EBUE using Pathfinder version 5 data (Demarcq, 2009). These differences 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, although an analysis of wind data over the same period did not pick up clear trends (*low confidence*, with respect to long-term wind trends; Demarcq, 2009; Barton et al., 2013).

How climate change will 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; Barton et al., 2013) in all regions. This debate is outlined in Box CC-UP. EBUE 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 (Barton et al., 2012). A full understanding of the consequences of ocean acidification for marine organisms and ecosystems is discussed elsewhere (Boxes CC-OA, CC-UP; Sections 6.2, 6.3.2; Kroeker et al., 2013; WGI AR5 Section 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. 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 occurring centrally, along the coasts of Mauritania (15°N to 20°N) and Morocco (21°N to 26°N). Total fish catches, comprising mainly coastal pelagic sardines, sardinellas, anchovies, and mackerel, have fluctuated around 2 million tonnes yr^{-1} since the 1970s (www.seaaroundus.org/lme/27.aspx). Contrasting with the other EBUE, fishing productivity is modest, probably partly due to the legacy of uncontrolled fishing in the 1960s (Arístegui et al., 2009).

Most observations suggest that the Canary Current has warmed since the early 1980s (Arístegui et al., 2009; Belkin, 2009; Demarcq, 2009; Barton et al., 2013), with analysis of HadISST1.1 data from 1950 to 2009 indicating warming of 0.53°C from 1950–2009 (p-value ≤ 0.05; Table 30-1). Gómez-Gesteira et al. (2008) suggest a 20 and 45% decrease in the strength of upwelling in winter and summer, respectively, from 1967 to 2006, consistent with a decrease in wind strength and direction over the past 60 years. More recently, Barton et al. (2013) show no clear increasing or decreasing trend in wind strength over the past 60 years, and a lack of agreement among wind trends and variability from different wind products (e.g., Pacific Fisheries Environmental Laboratory (PFEL), International Comprehensive Ocean-Atmosphere Data Set (ICOADS), Wave- and Anemometer-based Sea Surface Wind (WASWind)). Barton et al. (2013) present no evidence for changes in upwelling intensity, with the exception of upwelling off northwest Spain, where winds are becoming slightly less favorable. Alteration of wind direction and strength influences upwelling and hence nutrient concentrations; however, nutrient levels can also change in response to other variables such as the supply of iron-laden dust from the Sahara (Alonso-Pérez et al., 2011). There is *medium evidence* and *medium agreement* that primary production in the Canary Current has decreased over the past 2 decades (Arístegui et al., 2009; Demarcq, 2009), in contrast to the nearby upwelling region off northwest Spain where no significant trend was observed (Bode et al., 2011). Satellite chlorophyll records (Sea-viewing Wide Field-of-view Sensor (SeaWiFS), Moderate Resolution Imaging Spectrometer (MODIS)) are relatively short, making it difficult to distinguish the influence of warming oceans from longer term patterns of variability (Arístegui et al., 2009; Henson et al., 2010). Changing temperature has resulted in changes to important fisheries species. For example, Mauritanian waters have become more suitable as feeding and spawning areas for some fisheries species (e.g., *Sardinella aurita*) as temperatures increased (Zeeberg et al., 2008). Clear attribution of these changes depends on the linkage between the Azores High and global temperature, and on longer records for both physical and biological systems, as pointed out for data sets in general (Arístegui et al., 2009; Henson et al., 2010).

30.5.5.1.2. Benguela Current

The Benguela Current originates from the eastward-flowing, cold South Atlantic Current, flows northward along the southwest coast of Africa, 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 of 2.8 million tonnes yr^{-1} (www.seaaroundus.org/lme/29/1.aspx), before declines in the northern Benguela, due to overfishing and inter-decadal environmental variability, resulted in a reduced catch of around 1 million tonnes yr^{-1} (present) (Cury and Shannon, 2004; Heymans et al., 2004; Hutchings et al., 2009). Offshore commercial fisheries currently comprise sardine, anchovy, horse mackerel, and hake, while the inshore artisanal and recreational fisheries comprise a variety of fish species mostly caught by hook and line.

Most research on the Benguela Current has focused on fisheries and oceanography, with little emphasis on climate change. As with the other EBUE, strong interannual and inter-decadal variability in physical oceanography make the detection and attribution of biophysical trends to climate change difficult. Nevertheless, the physical conditions of the Benguela Current are highly sensitive to climate variability over a range of scales, 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*, despite *limited evidence* (Demarcq, 2009), that upwelling intensity and associated variables (e.g., temperature, nutrient, and O_2 concentrations) from the Benguela system will change as a result of climate change (Box CC-UP).

The temperature of the surface waters of the Benguela Current did not increase from 1950 to 2009 (p-value > +0.05; Table 30-1), although shorter records show an decrease in the south-central Benguela Current (0.35°C to 0.55°C per decade; Rouault et al., 2010) or an increase for the whole Benguela region (0.24°C; Belkin, 2009). These differences between short versus long records indicate the substantial influence of long-term variability on the Benguela system (Belkin, 2009). Information on other potential consequences of climate change within the Benguela system is sparse. SLR is similar to the global mean, although it has not been measured rigorously within the Benguela (Brundrit, 1995; Veitch, 2007). Although upwelling water in the northern and southern portions of the Benguela Current exhibits elevated and suppressed partial pressure of CO_2, respectively (Santana-Casiano et al., 2009), the consequences of changing upwelling intensity remain poorly explored with respect to ocean acidification. Finally, although periodic hypoxic events in the Benguela system are largely driven by natural advective processes, these may be exacerbated by future climate change (Monteiro et al., 2008; Bakun et al., 2010).

Despite its apparent sensitivity to environmental variability, there is *limited evidence* of ecological changes in the Benguela Current EBUE due to climate change (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. Trawl surveys of demersal fish and cephalopod species showed consistently predictable "hotspots" of species richness over a 20- to 30-year study period (the earliest surveys since 1984 off South Africa) that were associated with greater depths and cooler bottom waters (Kirkman et al., 2013). However, major changes in the structure and function of the demersal community have been shown in some parts of the Benguela Current EBUE in response to environmental change, for example, due predominantly to fishing pressure in the 1960s and environmental forcing in the early 2000s in the southern Benguela (Howard et al., 2007); therefore, changes driven by climate change may eventually affect the persistence of these biodiversity hotspots (Kirkman et al., 2013).

30.5.5.1.3. California Current

The California Current spans approximately 23° of latitude from central Baja California, Mexico, to central British Columbia, Canada, linking the North Pacific Current (West Wind Drift) with the North Equatorial and Kuroshio Currents to form the North Pacific Gyre. High productivity driven by advective transport and upwelling (Hickey, 1979; Chelton et al., 1982; Checkley and Barth, 2009; Auad et al., 2011) supports well-studied ecosystems and fisheries. Fish catches have been approximately 0.6 million tonnes yr^{-1} since 1950 (www.seaaroundus.org/lme/3.aspx), which makes it the lowest catch of the four EBUE. The ecosystem supports the foraging and reproductive activities of 2 to 6 million seabirds from around 100 species (Tyler et al., 1993). Marine mammals are diverse and relatively abundant, including recovering populations of humpback whales, among other species (Barlow et al., 2008).

The average temperature of the California Current warmed by 0.73°C from 1950 to 2009 (p-value ≤ 0.05; Table 30-1) and by 0.14°C to 0.80°C from 1985 to 2007 (Demarcq, 2009). Like other EBUE, the California Current is characterized by large-scale interannual and inter-decadal climate-ecosystem variability (McGowan et al., 1998; Hare and Mantua, 2000; Chavez et al., 2003; Checkley and Barth, 2009). 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 (Peterson and Schwing, 2003; 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 CC-UP). 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; Peterson and Schwing, 2003) 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).

There is *robust evidence* and *medium agreement* that the California Current has experienced a decrease in the number of upwelling events (23 to 40%), but an increase in duration of individual events, resulting in an increase of the overall magnitude of upwelling events from 1967 to 2010 (*high confidence*; Demarcq, 2009; Iles et al., 2012). This is consistent with changes expected under climate change yet remains complicated by the influence of decadal-scale variability (*low confidence*; Iles et al., 2012). Oxygen concentrations have also undergone large and consistent decreases from 1984 to 2006 throughout the California Current, with the largest relative decreases occurring below the thermocline (21% at 300 m). The hypoxic boundary layer (<60 µmol kg^{-1}) has also shoaled by 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 upwelling and productivity, which stimulates microbial activity and results in the drawdown of O_2 (*likely*, Bakun et al., 2010; but see also McClatchie et al., 2010; Koslow et al., 2011; WGI AR5 Section 3.8.3). These changes are *likely* to have reduced the available habitat for key benthic communities as well as fish and other mobile species (Stramma et al., 2010). Increasing microbial activity will also increase the partial pressure of CO_2, decreasing the pH and carbonate concentration of seawater. Together with the shoaling of the saturation horizon, these changes have increased the incidence of low O_2 and low pH water flowing onto the continental shelf (*high confidence*; 40 to 120 m; Feely et al., 2008), causing problems 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 EBUE, covering an area larger than the other three combined. It comprises the eastern edge of the 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 EBUE, the total Humboldt Current system has very high levels of fish production. Current catches are in line with a long-term average (since the 1960s) of 8 million tonnes yr^{-1} (www.seaaroundus.org/lme/13/1.aspx), although decadal-scale variations range from 2.5 to 13 million tonnes yr^{-1}. While anchovies currently contribute 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). This variability does not appear to be changing due to anthropogenic climate change. Thus, from the late 1970s to the 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 EBUE did not show an overall warming trend in SST over the last 60 years (p-value > 0.05; Table 30-1), which is consistent with 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 (Demarcq, 2009). The lack of a consistent warming signal may be due to the strong influence of adjacent ENSO activity exerting opposing drivers on upwelling and which, if they intensify, would decrease temperatures (*limited evidence*, *medium agreement*). Similar to the Canary Current EBUE, however, there was a significant increase in the temperatures of the warmest month of the year over the period 1950–2009 (p-value ≤ 0.05; Table 30-1).

Primary production is suppressed during warm El Niño events and amplified during cooler La Niña phases, these changes then propagate through to higher trophic levels (Chavez et al., 2003; Tam et al., 2008; Taylor et al., 2008). However, in addition to trophic changes, there is also a direct thermal impact on organisms, which varies depending on the thermal adaptation window for each species (*high confidence*). 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 other EBUE, there is lack of studies that have rigorously attempted to detect and attribute changes to anthropogenic climate change, although at least two studies (Mendelssohn and Schwing, 2002; Gutiérrez et al.,

2011) provide 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 1950–2009 (p-value > 0.05; Table 30-1). 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, and the fact that areas within the Humboldt Current EBUE may be showing different behaviors.

30.5.5.2. Key Risks and Vulnerabilities

EBUE are vulnerable to changes that influence the intensity of currents, upwelling, and mixing (and hence changes in SST, wind strength and direction), as well as O_2 content, carbonate chemistry, nutrient content, and the supply of organic carbon to deep offshore locations (*robust evidence*, *high agreement*; *high confidence*). The extent to which any particular EBUE is vulnerable to these factors depends on location (Figure 3 from Gruber, 2011) and other factors such as alternative 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 EBUE will respond to further climate change is uncertain (Box CC-UP; Rykaczewski and Dunne, 2010).

In the GCM ensembles examined (Table SM30-3), modest rates of warming (0.22°C to 0.93°C) occur within the four EBUEs in the near term. Over 2010–2099, however, EBUE SSTs warm by 0.07°C to 1.02°C under RCP2.6, and 2.52°C to 3.51°C under RCP8.5 (Table SM30-4). These high temperatures have the potential to increase stratification of the water column and substantially reduce overall mixing in some areas. In contrast, the potential strengthening of coastal wind systems would intensify upwelling and stimulate primary productivity through the increased injection of nutrients into the photic zone of the EBUE (Box CC-UP). Garreaud and Falvey (2009) explored how wind stress along the South American coast would change by 2100 under SRES B2 and A2 scenarios. Using an ensemble of 15 GCMs, southerly wind systems upwelling increased along the subtropical coast of South America, extending and strengthening conditions for upwelling.

Changes in the intensity of upwelling within the EBUE will drive fundamental changes to the abundance, distribution, and viability of resident organisms, although an understanding of their nature and direction is limited. In some cases, large-scale decreases in primary productivity and dependent fisheries are projected to occur for EBUE ecosystems (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, where it is *virtually certain* to increase microbial respiration and hence increase low O_2 stress (Weeks et al., 2002; Bakun et al., 2010). 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 EBUE is therefore whether or not upwelling will intensify and, if so, whether the negative consequences (e.g., reduced O_2 and elevated CO_2) associated with upwelling intensification will outweigh potential benefits from increased primary production and fisheries catch.

30.5.6. Subtropical Gyres

Subtropical gyres (STG) dominate the Pacific, Atlantic, and Indian Oceans (Figure 30-1a), and consist of large stable water masses that circulate clockwise (Northern Hemisphere) and anticlockwise (Southern Hemisphere) due to the Coriolis Effect. The oligotrophic areas at the core of the STG represent one of the largest habitats on Earth, contributing 21.2% of ocean primary productivity and 8.3% of the

Frequently Asked Questions

FAQ 30.4 | Will climate change increase the number of “dead zones” in the oceans?

Dissolved oxygen is a major determinant of the distribution and abundance of marine organisms. Dead zones are persistent hypoxic conditions where the water doesn’t have enough dissolved oxygen to support oxygen-dependent marine species. These areas exist all over the world and are expanding, with impacts on coastal ecosystems and fisheries (*high confidence*). Dead zones are caused by several factors, particularly eutrophication where too many nutrients run off coastal cities and agricultural areas into rivers that carry these materials out to sea. This stimulates primary production, leading to a greater supply of organic carbon, which can sink into the deeper layers of the ocean. As microbial activity is stimulated, there is a sharp reduction in dissolved oxygen levels and an increased risk of dead zones (*high confidence*). Climate change can influence the distribution of dead zones by increasing water temperature and hence microbial activity, as well as reducing mixing (i.e., increasing layering or stratification) of the Ocean, thereby reducing mixing of oxygen-rich surface layers into the deeper parts of the Ocean. In other areas, increased upwelling can lead to stimulated productivity, which can also lead to more organic carbon entering the deep ocean, where it is consumed, decreasing oxygen levels (*medium confidence*). Managing local factors such as the input of nutrients into coastal regions can play an important role in reducing the rate at which dead zones are spreading across the world’s oceans (*high agreement*).

global fish catch (Figure 30-1b; Table SM30-1). 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 (e.g., Sections 5.3-4, 29.3-5), region-wide issues and consequences are discussed here due to the strong linkages between ocean and coastal issues.

30.5.6.1. Observed Changes and Potential Impacts

The central portions of the STG are oligotrophic (Figure SM30-1). Temperatures within the STG of the North Pacific (NPAC), South Pacific (SPAC), Indian Ocean (IOCE), North Atlantic (NATL), and South Atlantic (SATL) have increased at rates of 0.020°C, 0.024°C, 0.032°C, 0.025°C, and 0.027°C yr^{-1} from 1998 to 2010, respectively (Signorini and McClain, 2012). This is consistent with increases observed from 1950 to 2009 (0.25°C to 0.67°C; Table 30-1). However, differences among studies done over differing time periods emphasize the importance of long-term patterns of variability. Salinity has decreased across the North and South Pacific STG (Figure 30-6c; WGI AR5 Section 3.3.3.1), consistent with warmer sea temperatures and an intensification of the hydrological cycle (Boyer, 2005).

The North and South Pacific STG have expanded since 1993 (*high confidence*), with these changes *likely* being the consequence of a combination of wind forcing and long-term variability (Parrish et al., 2000; WGI AR5 Section 3.6.3). Chlorophyll levels, as determined by remote-sensing of ocean color (Box CC-UP), have decreased in the NPAC, IOCE, and NATL by 9, 12, and 11%, respectively (p-value ≤ 0.5; Signorini and McClain, 2012) over and above the inherent seasonal and interannual variability from 1998 to 2010 (Vantrepotte and Mélin, 2011). Chlorophyll levels did not change in the remaining two gyres (SPAC and SATL, and confirmed for SPAC by Lee and McPhaden (2010) and Lee et al. (2010)). Furthermore, over the period 1998–2007, median cell diameter of key phytoplankton species 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 (McClain et al., 2004; Gregg et al., 2005; Polovina et al., 2008) and are influenced by seasonal and longer-term sources of variability (e.g., ENSO, PDO; Section 6.3.4; Figure 6-9). 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 (Box CC-PP) 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.

30.5.6.1.1. Pacific Ocean Subtropical Gyres

Pacific climate is heavily influenced by the position of the Intertropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ), which are part of the ascending branch of the Hadley circulation (WGI AR5 Section 14.3.1). These features are also strongly influenced by interannual to inter-decadal climate patterns of variability including ENSO and PDO. The current understanding of how ENSO and PDO will change as average global temperatures increase is not clear (*low confidence*; Collins et al., 2010; WGI AR5 Section 12.4.4.2). The position of both the ITCZ and SPCZ vary seasonally and with 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, along with the West Pacific Monsoon, determine the timing and extent of the wet and dry seasons in SPAC and NPAC sub-regions (Ganachaud et al., 2011). Tropical cyclones are prominent in the Pacific (particularly the western Pacific), and CBS sub-regions between 10° and 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 have been almost twice as many land-falling tropical cyclones in 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., IPO) and climate forcing (*high confidence*; Meehl et al., 2009). This change coincided with changes to total rainfall, rain days, and dry spells across the Pacific, with the direction of change depending on the location relative to the SPCZ. 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 northeast during El Niño (*high confidence*). The opposite is true during La Niña conditions. The consequences of changing rainfall on the countries of the Pacific STG are discussed in greater detail elsewhere (Sections 5.4, 29.3; Table 29-1). Although 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 (*very high confidence*; Hoegh-Guldberg and Salvat, 1995; Hoegh-Guldberg, 1999; Mumby et al., 2001; Baker et al., 2008; Donner et al., 2010). There are few, if any, scientific records of mass coral bleaching and mortality prior to this period (*high confidence*; 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 (*high confidence*; Bruno and Selig, 2007; Hughes et al., 2011; Sweatman et al., 2011; De'ath et al., 2012). The reasons for this decline are complex and involve non-climate change-related factors (e.g., coastal pollution and overfishing) as well as global warming and possibly acidification. A recent comprehensive analysis of the ecological consequences 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" (*high confidence*; Baker et al., 2008, p. 435). Increasing sea levels have also caused changes in seagrass and mangrove systems. Gilman et al. (2007) found a reduction in mangrove area with SLR, with the observed mean landward recession of three mangrove areas over 4 decades being 25, 64, and 72 mm yr^{-1}, 12 to 37 times faster than the observed rate of SLR. 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.

Changes in 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 distribution and recruitment in response to changes in sea temperature as result of ENSO demonstrate the close association of pelagic fish stocks and water temperature. The shift in habitat for top predators in the northeast Pacific was examined by Hazen et al. (2012), who used tracking data from 23 marine species and associated environmental variables to predict changes of up to 35% in core habitat for these species within the North Pacific. Potential habitats are predicted to contract for the blue whale, salmon shark, loggerhead turtle, and blue and mako sharks, while potential habitats for the sooty shearwater; black -footed albatross; leatherback turtle; white shark; elephant seal; and albacore, bluefin and yellowfin tuna are predicted to expand (Hazen et al., 2012). However, expansion of OMZs in the Pacific STG is predicted to compress habitat (depth) for hypoxia-intolerant species such as tuna (Stramma et al., 2010, 2012).

Reduction of ocean productivity of the STG (Sarmiento et al., 2004; Signorini and McClain, 2012) reduces the flow of energy to higher trophic levels such as those of pelagic fish (Le Borgne et al., 2011). The distribution and abundance of fisheries stocks such as tuna are 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 cooler 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, 2006). Projections of big-eye tuna (*T. obesus*) distributions under SRES A2 show an improvement in spawning and feeding habitats by 2100 in the eastern tropical Pacific and declines in the western tropical Pacific, leading to an eastern displacement of tuna stocks (Lehodey et al., 2008, 2010b).

30.5.6.1.2. Indian Ocean Subtropical Gyre

Like the Pacific Ocean, the Indian Ocean plays a crucial role in 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 seawater chemistry all 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 affected by record positive sea temperature anomalies seen in the Southern Hemisphere between February to April 1998 (*robust evidence*, *high agreement*; *high confidence*; Ateweberhan et al., 2011). Coral cover across the Western Indian Ocean declined by an average of 37.7% after the 1998 heat stress event (Ateweberhan et al., 2011). Responses to the anomalously warm conditions in 1998 varied between sub-regions, with the central Indian Ocean islands (Maldives, Seychelles, Chagos, and Lakshadweep) experiencing major decreases in coral cover directly after the 1998 event (from 40 to 53% coral cover in 1977–1997 to 7% in 1999–2000; *high confidence*; Ateweberhan et al., 2011). Coral reefs lining the islands of southern India and Sri Lanka experienced similar decreases in coral cover (45%, 1977–1997 to 12%, 1999–2000). Corals in the southwestern Indian Ocean (Comoros, Madagascar, Mauritius, Mayotte, Réunion, and Rodrigues) showed less impact (44%, 1977–1997 to 40%, 1999–2000). Recovery from these increases in mortality 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 are showing much higher rates (achieving a mean coral cover of 37% by 2001–2005; Ateweberhan et al., 2011). These changes to the population size of key reef-building species will 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 (*medium confidence*; Box CC-CR).

Fisheries that exploit tuna and other large pelagic species are very valuable to many small island states within the Indian Ocean. As with Pacific fisheries, the distribution and abundance of large pelagic fish in the Indian Ocean is greatly influenced by sea temperature. The anomalously high sea temperatures of 1997–1998 (leading to a deepening of the mixed layer in the west and a shoaling in the east) coincided with anomalously low primary production in the Western Indian Ocean and a major shift in tuna stocks (*high confidence*; Menard et al., 2007; Robinson et al., 2010). Fishing grounds in the Western Indian Ocean were deserted and fishing fleets underwent a massive shift toward the eastern basin, which was unprecedented for the tuna fishery (*high confidence*). As a result of these changes, many countries throughout the Indian Ocean lost significant tuna-related revenue (Robinson et al., 2010). In 2007, tuna fishing revenue was again reduced by strong surface warming and deepening of the mixed layer, and associated with a modest reduction in primary productivity in the west. These trends highlight the overall vulnerability of tuna fishing countries in the Indian Ocean to climate variability, a situation similar to that in the other major oceans of the world.

30.5.6.1.3. Atlantic Ocean Subtropical Gyres

SST has increased within the two STG of the Atlantic Ocean over the last 2 decades (Belkin, 2009; Signorini and McClain, 2012). Over longer periods of time (1950–2009), trends in average temperature are not significant for the North Atlantic STG (p-value > 0.05) while they remain so for the South Atlantic STG (*very likely*; 0.08°C per decade, p-value ≤ 0.05; Table 30-1). In both cases, however, temperatures in the coolest and warmest months increased significantly (Table 30-1). The difference between these studies (i.e., over 10 to 30 years vs. 60 years) emphasizes the importance of long-term patterns of variability in the North Atlantic region. Variability in SST at a period of about 60 to 80 years is associated with the Atlantic Multi-decadal Oscillation (AMO; Trenberth and Shea, 2006). Sea surface temperatures influence hurricane activity (*very likely*) with recent record SST associated with record hurricane activity in 2005 in the Atlantic (Trenberth and Shea, 2006) and mass coral bleaching and mortality in the eastern Caribbean (*high confidence*; Eakin et al., 2010). In the former case, analysis concluded that 0.1°C of the SST anomaly was attributable to the state of the AMO while 0.45°C was due to ocean warming as a result of anthropogenic influences (Trenberth and Shea, 2006).

These changes have influenced the distribution of key fishery species as well the ecology of coral reefs in Bermuda (Wilkinson and Hodgson, 1999; Baker et al., 2008) 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 (*high confidence*; Box CC-CR; Figure 30-10). As with the other STG, phytoplankton communities and pelagic fish stocks are sensitive to temperature changes that have occurred over the past several decades. Observation of these changes has enabled development of models that have a high degree of accuracy in projecting the distribution and abundance of these elements within the Atlantic region in general (Cheung et al., 2011).

30.5.6.2. Key Risks and Vulnerabilities

SSTs of the vast STGs of the Atlantic, Pacific, and Indian Oceans are increasing, which is *very likely* to increase stratification of the water column. In turn, this is *likely* to reduce surface concentrations of nutrients and, consequently, primary productivity (*medium confidence*; Box CC-PP). Warming is projected to continue (Table SM30-4), with substantial increases in the vulnerability and risk associated with systems that have been observed to change so far (*high confidence*; Figure 30-12). Under RCP2.6, the temperatures of the STG are projected to increase by 0.17°C to 0.56°C in the near term (over 2010–2039) and between –0.03°C to 0.90°C in the long term (over 2010–2099) (Table SM30-4). Under RCP8.5, however, surface temperatures of the world's STG are projected to be 0.45°C to 0.91°C warmer in the near term and 1.90°C to 3.44°C warmer in the long term (Table SM30-4). 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 O_2 concentrations. It is not clear as to how longer-term sources of variability such as ENSO and PDO will change (WGI AR5 Sections 14.4, 14.7.6) and ultimately influence these trends.

The world's most oligotrophic ocean sub-regions are *likely* to continue to expand over coming decades, with consequences for ecosystem services such as gas exchange, fisheries, and carbon sequestration. 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 (~RCP6.0 to RCP8.5; see also Figure 1.5 from Rogelj et al., 2012). Model projections indicated the STG expanding 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. In the North Pacific STG, the total primary production is projected to decrease by 10 to 20% and large fish catch by 19 to 29% by 2100 under SRES A2 (Howell et al., 2013; Woodworth-Jefcoats et al., 2013). However, our understanding of how large-scale eddy systems will change in a warming world is incomplete, as are the implications for primary productivity of these large and important systems (Boxes CC-PP, CC-UP).

Understanding how storm frequency and intensity will change represents a key question for many countries and territories within the various STG. 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 (WGI AR5 Section 14.6). 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 will change within all STG is uncertain at this point. However, an intensifying hydrological cycle is expected to increase precipitation in many areas (*high confidence*; WGI AR5 Sections 2.5, 14.2), although longer droughts are also expected in other STG (*medium confidence*). Changes in the hydrological cycle impact coastal ecosystems, increasing damage through coastal flooding and physical damage from storm waves (Mumby et al., 2011). Improving our understanding of how weather systems associated with features such as the SPCZ (WGI AR5 Section 14.3.1) will vary is critical to climate change adaptation of a large number of nations associated with the STG. Developing an understanding of how ocean temperature, climate systems such as the SPCZ and ITCZ, and climate change and variability (e.g., ENSO, PDO) interact will be essential in this regard. For example, variability in the latitude of the SPCZ is projected to increase, possibly leading to more extreme events in Pacific Island countries (Cai et al., 2012).

The consequences of projected sea temperatures on the frequency of coral bleaching and mortality within key sub-regions of the STG are outlined in Box CC-CR and Figures 30-10 and SM30-3. As with other sub-regions (particularly CBS, STG, and SES) 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 to 2 years by 2100 (*virtually certain*; Box CC-CR; Figures 30-10, SM30-3). Coral-dominated reef ecosystems (areas with more than 30% coral cover) are *very likely* to disappear under these circumstances by the mid part of this century (van Hooidonk et al., 2013). The loss of substantial coral communities has implications for the three-dimensional structure of coral reefs (Box CC-CR) and the role of the latter as habitat for organisms such as fish (Hoegh-Guldberg, 2011; Hoegh-Guldberg et al., 2011a; Pratchett et al., 2011a; Bell et al., 2013b).

The consequences of increasing sea temperature can be exacerbated by increasing ocean acidification, with potential implications for reef calcification (*medium confidence*; Kleypas et al., 1999; Hoegh-Guldberg et al., 2007; Doney et al., 2009), reef metabolism and community calcification (Dove et al., 2013), and other key ecological processes (Pörtner et al., 2001, 2007; Munday et al., 2009). Ocean pH within the STG will continue to decrease as atmospheric CO_2 increases, bringing pH within the STG to 7.9 and 7.7 at atmospheric concentrations of 450 ppm and 800 ppm, respectively (Figure SM30-2a; Box CC-OA). Aragonite saturation states will decrease to around 1.6 (800 ppm) and 3.3 (450 ppm; Figure SM30-2b). Decreasing carbonate ion concentrations and saturation states pose serious risks to other marine calcifiers such as encrusting coralline algae, coccolithophores (phytoplankton), and a range of benthic 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 (Section 29.3.1.2; Waycott et al., 2007, 2011). Many of the negative consequences for coral reefs, mangroves, and seagrass meadows are *likely* to have negative consequences for dependent coastal fisheries (through habitat destruction) and tourism industries (*medium confidence*; Bell et al., 2011a, 2013a; Pratchett et al., 2011a,b).

Populations of key large pelagic fish are projected to move many hundreds of kilometers east of where they are today in the Pacific STG (*high confidence*; Lehodey et al., 2008, 2010a, 2011, 2013), with implications for income, industry, and food security across multiple Pacific Island nations (*high confidence*; Cheung et al., 2010; McIlgorm et al., 2010; Bell et al., 2011b, 2013a; Section 7.4.2; Tables 29-2, 29-4). These predictions of species range displacements, contractions, and expansions in response to anticipated changes in the Ocean (Box CC-MB) present both a challenge and an opportunity for the development of large-scale management strategies to preserve these valuable species. Our understanding of the consequences of reduced O_2 for pelagic fish populations is not clear, although there is *high agreement* on the potential physiological outcomes (Section 6.3.3). Those species that are intolerant to hypoxia, such as skipjack and yellowfin tuna (Lehodey et al., 2011), will have their depth range compressed in the Pacific STG, which will increase their vulnerability to fisheries and reduce overall fisheries habitat and productivity (*medium confidence*; Stramma et al., 2010, 2011). Despite the importance of these potential changes, our understanding of the full range of consequences is *limited* at this point.

30.5.7. Deep Sea (>1000 m)

Assessments of the influence of climate change on the Deep Sea (DS) are challenging because of difficulty of access and scarcity of long-term, comprehensive observations (Smith, Jr. et al., 2009). The size of this habitat is also vast, covering well over 54% of the Earth's surface and stretching from the top of the mid-oceanic ridges to the bottom of deep ocean trenches (Smith, Jr. et al., 2009). The fossil record in marine sediments reveals that the DS has undergone large changes in response to climate change in the past (Knoll and Fischer, 2011). The paleo-skeletal record shows that it is the rate, not just the magnitude, of climate change (temperature, O_2, and CO_2) that is critical to marine life in DS. The current rate of change 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 DS ecosystems experience physical climate change. The second is the rapid rate at which organic matter enters the deep ocean from primary productivity generated at the surface of the Ocean, which represents a critical food supply to DS animals (Smith, Jr. and Kaufmann, 1999; Smith, Jr. et al., 2009). It can also represent a potential risk in some circumstances where the flux of organic carbon into the deep ocean, coupled with increased sea temperatures, can lead to anoxic areas (dead zones) as metabolism is increased and O_2 decreased (Chan et al., 2008; Stramma et al., 2010).

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 (*very high confidence*; WGI AR5 Section 3.2), although smaller yet significant changes are occurring at depth. The DS environment is typically cold (~–0.5°C to 3°C; Smith et al., 2008), although abyssal temperatures in the SES can be higher (e.g., Mediterranean DS ~12°C; Danovaro et al., 2010). In the latter case, DS organisms 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 O_2-demand window of tolerance (Pörtner, 2010) and therefore it is *likely* that shifts in the distribution of DS species and regional extinctions will occur. Warming over multiple decades has been observed below 700 m (Levitus et al., 2005, 2009), with warming being minimal at mid-range depths (2000 to 3000 m), and increasing toward the sea floor in some sub-regions (e.g., Southern Ocean; WGI AR5 Chapter 3). For the deep Atlantic Ocean, the mean age of deep waters (mean time since last exposure to the atmosphere) is approximately 250 years; the oldest deep waters of the Pacific Ocean are >1000 years old. The patterns of ocean circulation are clearly revealed by the penetration of tracers and the signal of CO_2 released from burning fossil fuel penetrating into the abyss (Sabine et al., 2004). It will take many centuries for full equilibration of deep ocean waters and their ecosystems with recent planetary warming and CO_2 levels (Wunsch and Heimbach, 2008).

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

Particulate organic carbon is exported from the surface to deeper layers of the Ocean (>500 m) with an efficiency of between 20 and 50% (Buesseler et al., 2007), much of it being recycled by microbes before it reaches 1000 m (Smith, Jr. et al., 2009). The export of organic carbon is dependent on surface net primary productivity, which is *likely* to vary (Box CC-PP), influencing the supply of food to DS (Laws et al., 2000; Smith et al., 2008). Warming of intermediate waters will also increase respiration at mid-water depths, reducing the flux of organic carbon. Our understanding of other components of DS ecosystems is also relatively poor. For example, there is *limited evidence* and *limited agreement* as to how ocean warming and acidification are *likely* to affect ecosystems such as those associated with hydrothermal vents (Van Dover, 2012).

Oxygen concentrations are decreasing in the DS (Stramma et al., 2008; Helm et al., 2011a). Although the largest signals occur at intermediate water depths < 1000 m (Nakanowatari et al., 2007; Whitney et al., 2007; Falkowski et al., 2011), some waters >1000 m depth are also experiencing a decline (Jenkins, 2008). The quantity of dissolved O_2

30

throughout the Ocean will be reduced with 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 O_2 solubility at higher temperatures will have additive consequences for the decline of O_2 (*high confidence*) even in the DS. The DS waters are relatively well oxygenated owing to the higher solubility of O_2 in colder waters and the low supply rate of organic matter to great depths. The availability of oxygen to marine animals is governed by a combination of concentration, temperature, pressure, and related properties such as diffusivity. Analysis by Hofmann et al. (2013) reveals that the supply potential of oxygen to marine animals in cold deep waters is similar to that at much shallower depths (*very high confidence*).

Anthropogenic CO_2 has penetrated to at least 1000 m in all three ocean basins (particularly the Atlantic; Doney et al., 2009). Further declines of calcite and aragonite in already under-saturated DS water will presumably decrease biological carbonate structure formation and increase dissolution, as has happened many times in Earth's past (*high confidence*; Zeebe and Ridgwell, 2011). Some cold-water corals (reported down to 3500 m) already exist in waters under-saturated with respect to aragonite (Lundsten et al., 2009). Although initial investigations suggested that ocean acidification (reduced by 0.15 and 0.30 pH units) would result in a reduction in the calcification rate of deep water corals (30 and 56%, respectively), accumulating evidence shows that ocean acidification may have far less impact than previously anticipated on the calcification of some deep water corals (*limited evidence*, *medium agreement*; *low confidence*) although it may reduce important habitats given that dead unprotected coral mounds are *likely* to dissolve in under-saturated waters (Thresher et al., 2011; Form and Riebesell, 2012; Maier et al., 2013).

30.5.7.2. Key Risks and Vulnerabilities

Rising atmospheric CO_2 poses a risk to DS communities through increasing temperature, decreasing O_2 and pH, and changing carbonate chemistry (*high confidence*; Keeling et al., 2010). Risks associated with the DS have implications for the Ocean and planet given the high degree of inherent dependency and connectivity. The resulting changes to the flow of organic carbon to some parts of the DS (e.g., STG) are *very likely* to affect DS ecosystems (*medium confidence*; Smith et al., 2008). As with the Ocean 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 analysis in this chapter and elsewhere in AR5 has identified a wide range of physical, chemical, and ecological components that have changed over the last century (Box CC-MB). Figure 30-11 summarizes a number of examples from the Ocean as a region together with the degree of confidence in both the detection and attribution steps. For ocean warming and acidification, confidence is *very high* that changes are being detected and that they are due to changes to the atmospheric GHG content. There is considerable confidence in both the detection (*very high confidence*) and attribution (*high confidence*) of mass coral bleaching and mortality, given the well-developed understanding of environmental processes and physiological responses driving these events (Box CC-CR; Section 6.3.1). For other changes, confidence is lower, either because detection of changes has been difficult, or monitoring programs are not long established (e.g., field evidence of declining calcification), or because detection has been possible but models are in conflict (e.g., wind-driven upwelling). The detection and attribution of recent changes is discussed in further detail in Sections 18.3.3-4.

30.6. Sectoral Impacts, Adaptation, and Mitigation Responses

Human welfare is highly dependent on ecosystem services provided by the Ocean. Many of these services are provided by coastal and shelf areas, and are consequently addressed in other chapters (e.g., Sections 5.4.3, 7.3.2.4, 22.3.2.3). Oceans contribute provisioning (e.g., food, raw materials; see Section 30.6.2.1), regulating (e.g., gas exchange, nutrient recycling, carbon storage, climate regulation, water flux), supporting (e.g., habitat, genetic diversity), and cultural (e.g., recreational, religious) services (MEA, 2005; Tallis et al., 2013). The accumulating evidence indicating that 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 (Rockström et al., 2009; Ruckelshaus et al., 2013). Discussion here is restricted to environmental, economic, and social sectors that have direct relevance to the Ocean—namely natural ecosystems, fisheries and aquaculture, tourism, shipping, oil and gas, human health, maritime security, and renewable energy. The influences of climate change on Ocean sectors will be mediated through simultaneous changes in multiple environmental and ecological variables (see Figure 30-12), and the extent to which changes can be adapted to and/or risks mitigated (Table 30-3). Both short- and longer-term adaptation is necessary to address impacts arising from warming, even under the lowest stabilization scenarios assessed.

Sectoral approaches dominate resource use and management in the Ocean (e.g., 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, although land-based pollution, commercial fishing, invasive species, coastal habitat modification, and commercial activities such as shipping all rank high in many places around the world (e.g., Sections 5.3.4, 30.5.3-4; Halpern et al., 2009, 2010). 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 improve overall ecosystem condition (e.g., Halpern et al., 2010; Kelly et al., 2011). The latter has often been seen as a potential strategy for reducing negative consequences of climate impacts on marine ecosystems by boosting ecosystem resilience, thus buying time while the core issue of reducing GHG emissions is tackled (West et al., 2009).

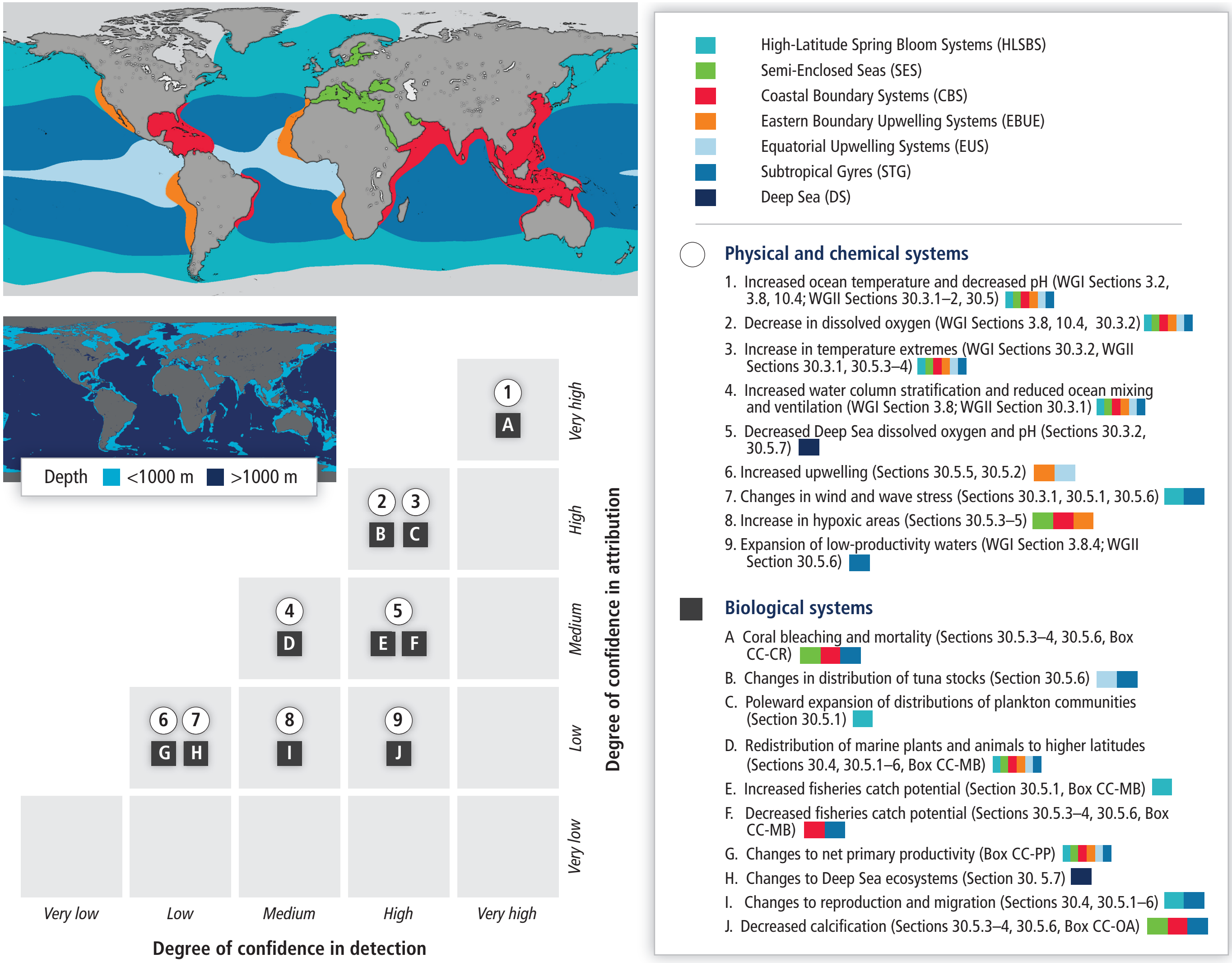


Figure 30-11 | Expert assessment of degree of confidence in detection and attribution of physical and chemical changes (white circles) and ecological changes (dark gray squares) across sub-regions, as designated in Figure 30-1a, and processes in the Ocean (based on evidence explored throughout Chapter 30 and elsewhere in AR5). Further explanation of this figure is given in Sections 18.3.3-4 and 18.6.

30.6.1. Natural Ecosystems

Adaptation in natural ecosystems may occur autonomously, such as tracking shifts in species' composition and distributions (Poloczanska et al., 2013), or engineered by human intervention, such as assisted dispersal (Section 4.4.2.4; Hoegh-Guldberg et al., 2008). Currently, adaptation strategies for marine ecosystems include reducing additional stressors (e.g., maintaining water quality, adapting fisheries management) and maintaining resilience ecosystems (e.g., Marine Protected Areas), and are moving toward whole-of-ecosystem management approaches. Coral reefs, for example, will recover faster from mass coral bleaching and mortality if healthy populations of herbivorous fish are maintained (*medium confidence*; Hughes et al., 2003), indicating that reducing overfishing will help maintain coral-dominated reef systems while the international community reduces the emissions of GHGs to stabilize global temperature and ocean chemistry.

Approaches such as providing a formal valuation of ecological services from the Ocean have potential to facilitate adaptation by underpinning more effective governance, regulation, and ocean policy while at the same time potentially improving management of these often vulnerable services through the development of market mechanisms and incentives (Beaudoin and Pendleton, 2012). 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 owing to their complexity, problems such as double counting, and the value of non-market goods and services arising from marine ecosystems generally (Fu et al., 2011; Beaudoin and Pendleton, 2012).

"Blue Carbon" is defined as the organic carbon sequestered by marine ecosystems such as phytoplankton, mangrove, seagrass, and salt marsh ecosystems (Laffoley and Grimsditch, 2009; Nellemann et al., 2009). In this respect, Blue Carbon will provide opportunities for both adaptation to, and mitigation of, climate change if key uncertainties in inventories, methodologies, and policies for measuring, valuing, and implementing Blue Carbon strategies are resolved (McLeod et al., 2011). Sediment surface levels in vegetated coastal habitats can rise several meters over thousands of years, building carbon-rich deposits (Brevik and Homburg,

Examples of projected impacts and vulnerabilities associated with climate change in Ocean regions

(1) Expansion of low-productivity areas as a consequence of thermal stratification and changes in wind stress. (*Low*)

(2) Northward expansion of plankton, invertebrate, and fish communities with warming. Increase in fish biomass at high latitude fringes. (*High*)

(6) Decline in dissolved oxygen through changes in oxygen solubility (temperature), and ocean ventilation and circulation. (*Medium*)

(7) Expansion of seasonally hypoxic waters due to thermal stratification and eutrophication. Mass coral bleaching events leading to degradation of coral reefs and loss of associated biodiversity. (*High*)

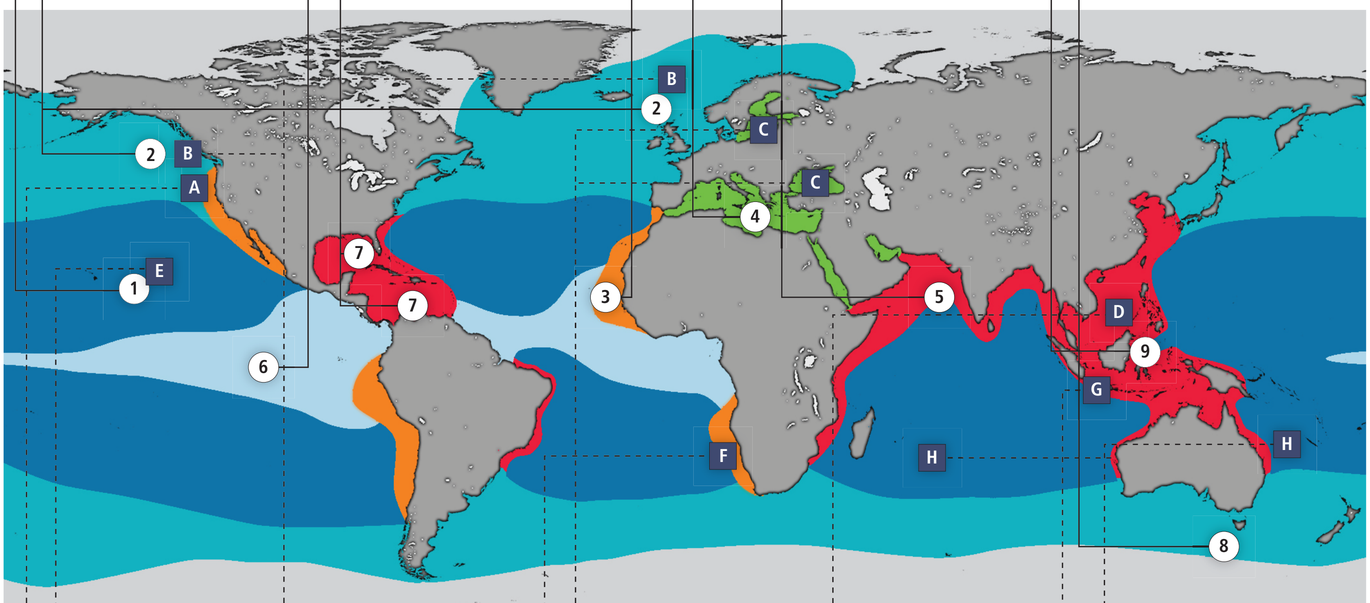
(3) Upwelling, hence productivity, changes as a result of climate variability, particularly wind stress variability. (*Low*)

(4) Spread of tropical species originating from Indian and Atlantic Oceans. Increased frequency of mass mortality events of benthic plants and animals linked to extreme temperature events. (*High*)

(5) Declining dissolved oxygen concentrations and expansion of Oxygen Minimum Zones (OMZ). (*High*)

(9) Mass coral bleaching and mortality in response to warming as well as temperature-driven decline in growth rates of some corals leading to degradation of coral reefs and loss of associated biodiversity. (*Very high*)

(8) Shoaling of aragonite saturation horizon reduces biological calcification and alters plankton communities. (*High*)



(E) Warming leads to decline in primary production and reductions in fish catch. (*Low*)

(A) Acidification of seasonally upwelling waters impacts shellfish aquaculture. (*Medium*)

(B) Increased fish catches at high-latitude fringes with economic disruptions and jurisdictional tensions as some fish stocks shift distributions. (*Medium*)

(C) Thermal stratification and eutrophication reduces dissolved oxygen with impacts on fish stocks. (*Medium*)

(F) Increase in variability of upwelling in some EBUEs adds uncertainty to fisheries management. (*Medium*)

(D) Sea level rise modifies coastlines and increases flooding, challenging aquaculture such as shrimp farms. (*Medium*)

(H) Temperature-driven shifts in stocks of large pelagic fish create winners and losers among country and island economies. (*High*)

(G) Degradation of coral reefs and associated fish stocks as the extent and intensity of mass coral bleaching and mortality increases, increasing risks to regional food security. (*High*)

Examples of risks to fisheries from observed and projected impacts

- High-Latitude Spring Bloom Systems
- Semi-Enclosed Seas
- Coastal Boundary Systems
- Eastern Boundary Upwelling Systems
- Equatorial Upwelling Systems
- Subtropical Gyres

Figure 30-12 | Top: Examples of projected impacts and vulnerabilities associated with climate change in Ocean sub-regions. Bottom: Examples of risks to fisheries from observed and projected impacts across Ocean sub-regions. Words in parentheses indicate level of confidence. Details of sub-regions are given in Table 30-1a and Section 30.1.1.

2004; Lo Iacono et al., 2008). The degradation of coastal habitats not only liberates much of the carbon associated with vegetation loss, but can also release and oxidize buried organic carbon through erosion of cleared coastlines (*high confidence*; Duarte et al., 2005). 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 CO_2 emissions arising from destruction of these three ecosystems was equivalent to 3 to 19% of the emissions generated by deforestation globally, with economic damages estimated to be US$6 to US$42 billion annually. Similarly, Luisetti et al. (2013) estimate the carbon stock of seagrass and salt marshes in Europe, representing less than 4% of global carbon stocks in coastal vegetation, was valued at US$180 million, at EU Allowance price of €8/tCO_2 in June 2012. A reversal of EU Environmental Protection Directives could result in economic losses of US$1 billion by 2060. Blue Carbon strategies can also be justified in light of the numerous ecosystem services these ecosystems provide, such as protection against coastal erosion and storm damage, and provision of habitats for fisheries species (Section 5.5.7).

30.6.2. Economic Sectors

30.6.2.1. Fisheries and Aquaculture

The Ocean provided 64% of the production supplied by world fisheries (capture and aquaculture) in 2010, amounting to 148.5 million tonnes of fish and shellfish (FAO, 2012). This production, valued at US$217.5 billion, supplied, on average, 18.6 kg of protein-rich food per person to an estimated population of 6.9 billion (FAO, 2012). Marine capture fisheries supplied 77.4 million tonnes with highest production from the northwest Pacific (27%), west-central Pacific (15%), northeast Atlantic (11%), and southeast Pacific (10%) (FAO, 2012). World aquaculture production (59.9 million tonnes in 2010) is dominated by freshwater fishes; nevertheless, marine aquaculture supplied 18.1 million tonnes (30%) (FAO, 2012).

Marine capture fisheries production increased from 16.8 million tonnes in 1950 to a peak of 86.4 million tonnes in 1996, then declined before stabilizing around 80 million tonnes (FAO, 2012). The stagnation of marine capture fisheries production is attributed to full exploitation of around 60% of the world's marine fisheries and overexploitation of 30% (estimates for 2009) (FAO, 2012). Major issues for industrial fisheries include illegal, unreported, and unregulated fishing; ineffective implementation of monitoring, control, and surveillance; and overcapacity in fishing fleets (World Bank and FAO, 2008; FAO, 2012). Such problems are being progressively addressed in several developed and developing countries (Hilborn, 2007; Pitcher et al., 2009; Worm 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.

The significance of marine capture fisheries is illustrated powerfully by the number of people engaged in marine small-scale fisheries (SSF) in developing countries. SSF account for around half of the fish harvested 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). SSF are often characterized by large numbers of politically weak fishers operating from decentralized localities, with poor governance and insufficient data to monitor catches effectively (Kurien and Willmann, 2009; Cochrane et al., 2011; Pomeroy and Andrew, 2011). For these SSF, management that aims to avoid further depletion of overfished stocks may be more appropriate in the short-term than management aimed at maximizing sustainable production. These aims are achieved through adaptive management by (1) introduction of 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); (2) flexible modification of these controls through monitoring (Plagányi et al., 2013); and (3) investing in the social capital and institutions needed for communities and governments to manage SSF (Makino et al., 2009; Pomeroy and Andrew, 2011).

Changes to ocean temperature, chemistry, and other factors are generating new challenges for fisheries resulting in loss of coastal and oceanic habitat (Hazen et al., 2012; Stramma et al., 2012), the movement of species (Cheung et al., 2011), the spread and increase of disease and invading species (Ling, 2008; Raitsos et al., 2010; Chan et al., 2011), and changes in primary production (Chassot et al., 2010). There is *medium evidence* and *medium 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 (Section 7.2.1.2). The risks to ecosystems and fisheries vary from region to region (Section 7.3.2.4). Dynamic bioclimatic envelope models under SRES A1B project potential increases in fisheries production at high latitudes, and potential decreases at lower latitudes by the mid-21st century (Cheung et al., 2010; Section 6.5). Overall, warming temperatures are projected to shift optimal environments for individual species polewards and redistribute production; however, changes will be region specific (Cheung et al., 2010; Merino et al., 2012).

Fisheries, in particular shellfish, are also vulnerable to declining pH and carbonate ion concentrations. As a result, the global production of shellfish fisheries is *likely* to decrease (Cooley and Doney, 2009; Pickering et al., 2011) with further ocean acidification (*medium confidence*; Sections 6.3.2, 6.3.5, 6.4.1.1; Box CC-OA). Impacts may be first observed in EBUE where upwelled water is already relatively low in O_2 and under-saturated with aragonite (Section 30.5.5). Seasonal upwelling of acidified waters onto the continental shelf in the California Current region has recently affected oyster hatcheries along the coast of Washington and Oregon (Barton et al., 2012; Section 30.5.5.1.1). Whether declining pH and aragonite saturation due to climate change played a role is unclear; however, future declines will increase the risk of such events occurring.

Most marine aquaculture species are sensitive to changing ocean temperature (Section 6.3.1.4; exposed through pens, cages, and racks placed directly in the sea, utilization of seawater in land-based tanks, collection of wild spat) and, for molluscs particularly, changes in carbonate chemistry (Turley and Boot, 2011; Barton et al., 2012; Section 6.3.2.4). Environmental changes can therefore impact farm profitability, depending on target species and farm location. For example, a 1°C rise in SST is projected to shift production of Norwegian salmonids further north but may increase production overall (Hermansen and Heen, 2012). Industries for non-food products, which can be important for regional livelihoods such as Black Pearl in Polynesia, are also affected by rising SST. Higher temperatures are known to affect the quality of pearl nacre, and can increase levels of disease in adult oysters (Pickering et al., 2011; Bell et al., 2013b). Aquaculture production is also vulnerable to extreme events such as storms and floods (e.g., Chang et al., 2013). Flooding and inundation by seawater may be a problem to shore facilities on low-lying coasts. For example, shrimp farming operations in the tropics will be challenged by rising sea levels, which will be exacerbated by mangrove encroachment and a reduced ability for thorough-drying of ponds between crops (Della Patrona et al., 2011).

The impacts of climate change on marine fish stocks are expected to affect the economics of fisheries and livelihoods in fishing nations through changes in the price and value of catches, fishing costs, income to fishers and fishing companies, national labor markets, and industry re-organization (Sumaila et al., 2011; Section 6.4.1). A study of the potential vulnerabilities of national economies to the effects of climate change on fisheries, in terms of exposure to warming, relative importance of fisheries to national economies and diets, and limited societal capacity to adapt, concluded that a number countries including Malawi, Guinea, Senegal, Uganda, Sierra Leone, Mozambique, Tanzania, Peru, Colombia, Venezuela, Mauritania, Morocco, Bangladesh, Cambodia, Pakistan, Yemen, and Ukraine are most vulnerable (Allison et al., 2009).

Aquaculture production is expanding rapidly (Bostock et al., 2010) and will play an important role in food production and livelihoods as the human demand for protein grows. This may also add pressure on capture fisheries (FAO, 2012; Merino et al., 2012). Two-thirds of farmed food fish production (marine and freshwater) is achieved with the use of feed derived from wild-harvested, small, pelagic fish and shellfish. Fluctuations in the availability and price of fishmeal and fish oil for feeds, as well as their availability, pose challenges for the growth of sustainable aquaculture production, particularly given uncertainties in changes in EBUE upwelling dynamics to climate change (Section 30.5.5). Technological advances and changes in management such as increasing feed efficiencies, using alternatives to fishmeal and fish oil, and farming of herbivorous finfish, coupled with economic and regulatory incentives, will reduce the vulnerability of aquaculture to the impacts of climate change on small, pelagic fish abundance (Naylor et al., 2009; Merino et al., 2010; FAO, 2012).

The challenges of optimizing the economic and social benefits of both industrial fisheries and SSF and aquaculture operations, which often 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, adaptation options include establishment of early warning systems to aid decision making, diversification of enterprises, and development of adaptable management systems (Chang et al., 2013). Vulnerability assessments that link oceanographic, biological, and socioeconomic systems can be applied to identify practical adaptations to assist enterprises, communities, and households to reduce the risks from climate change and capitalize on the opportunities (Pecl et al., 2009; Bell et al., 2013b; Norman-López et al., 2013). The diversity of these adaptation options, and the policies needed to support them, are illustrated by the examples in the following subsections.

30.6.2.1.1. Tropical fisheries based on large pelagic fish

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 more than 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 (FAO, 2012; Bell et al., 2013a). Increasing sea temperatures and changing patterns of upwelling are projected to cause shifts in the distribution and abundance of pelagic top predator fish stocks (Sections 30.5.2, 30.5.5-6), with potential to create "winners" and "losers" among island economies as catches of the transboundary tuna stocks change among and within their exclusive economic zones (EEZs; Bell et al., 2013a,b).

A number of practical adaptation options and supporting policies have been identified to minimize the risks and maximize the opportunities associated with the projected changes in distribution of the abundant skipjack tuna in the tropical Pacific (Bell et al., 2011b, 2013a; Lehodey et al., 2011; Table 30-2). 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; and (5) the eventual restructuring of regional fisheries management organizations to help coordinate management measures across the entire tropical Pacific. Efforts to ensure provision of operational-level catch and effort data from all industrial fishing operations will improve models for projecting redistribution of tuna stocks and quotas under climate change (Nicol et al., 2013; Salinger et al., 2013). 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. Small-scale fisheries

Small-scale fisheries (SSF) account for 56% of catch and 91% of people working in fisheries in developing countries (Mills et al., 2011). SSF are fisheries that tend to operate at family or community level, have low levels of capitalization, and make an important contribution to food security and livelihoods. They are often dependent on coastal ecosystems, such as coral reefs, that provide habitats for a wide range of harvested fish and invertebrate species. Despite their importance to many developing countries, such ecosystems are under serious pressure from human activities including deteriorating coastal water quality, sedimentation, ocean warming, overfishing, and acidification (Sections 7.2.1.2, 30.3, 30.5; 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 in place

Table 30-2 | Examples of priority adaptation options and supporting policies to assist Pacific Island countries and territories to minimize the threats of climate change to the socioeconomic benefits derived from pelagic and coastal 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 do not exceed costs in the short term but accrue under longer term climate change (modified from Bell et al., 2013b). WCPFC = Western and Central Pacific Fisheries Commission.

	Adaptation options	Supporting policies
Economic development	• Full implementation of the vessel day scheme to control fishing effort by the Parties to the Nauru Agreement[a] (W–W) • Diversifying sources of fish for canneries in the region and maintaining trade agreements, e.g., an economic partnership agreement with the European Union (W–W) • Continued conservation and management measures for all species of tuna to maintain stocks at healthy levels and make these valuable species more resilient to climate change (W–W) • Energy efficiency programs to assist fleets to cope with oil price rises and minimize CO_2 emissions and reduce costs of fishing further afield as tuna distributions shift east (W–W) • Pan-Pacific tuna management through merger of the WCPFC and Inter-American Tropical Tuna Commission to coordinate management measures across the tropical Pacific (L–W)	• Strengthen national capacity to administer the vessel day scheme. • 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 subregional concentrations of tuna in archipelagic waters beyond the mandate of WCPFC. • Require all industrial tuna vessels to provide operational-level catch and effort data to improve the models for redistribution of tuna stocks during climate change.
Food security	• Manage catchment vegetation to reduce transfer of sediments and nutrients to coasts to reduce damage to adjacent coastal coral reefs, mangroves, and seagrasses that support coastal fisheries (W–W). • 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). • Provide for migration of fish habitats by prohibiting construction adjacent to mangroves and seagrasses and installing culverts beneath roads to help the plants colonize landward areas as sea level rises (L–W). • Sustain and diversify catches of demersal coastal fish to maintain the replenishment potential of all stocks (L–W). • Increase access to tuna caught by industrial fleets through storing and selling tuna and by-catch landed at major ports to provide inexpensive fish for rapidly growing urban populations (W–W). • Install fish aggregating devices close to the coast to improve access to fish for rural communities as human populations increase and demersal fish decline (W–W). • Develop coastal fisheries for small pelagic fish species, e.g., mackerel, anchovies, pilchards, sardines, and scads (W–W?). • Promote simple post-harvest methods, such as traditional smoking, salting, and drying, to extend the shelf life of fish when abundant catches are landed (W–W).	• 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. • Minimize 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 food security 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 anchored inshore fish aggregating devices as part of national infrastructure for food security.
Livelihoods	• Relocate pearl farming operations to deeper water and to sites closer to coral reefs and seagrass/algal areas where water temperatures and aragonite saturation levels are likely to be more suitable for good growth and survival of pearl oysters and formation of high-quality pearls (L–W). • Raise the walls and floor of shrimp ponds so that they drain adequately as sea level rises (L–W). • Identify which shrimp ponds may need to be rededicated to producing other commodities (L–W).	• Provide incentives for aquaculture enterprises to assess risks to infrastructure so that farming operations and facilities can be "climate-proofed" and relocated if necessary. • Strengthen environmental impact assessments for coastal aquaculture activities to include the additional risks posed by climate change. • Develop partnerships with regional technical agencies to provide support for development of sustainable aquaculture.

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

(Sections 30.5.4, 30.5.6). For example, coral losses around Pacific Islands are projected to be as high as 75% by 2050 (Hoegh-Guldberg et al., 2011a). Even under the most optimistic projections (a 50% loss of coral by 2050), changes to state of coral reefs (Box CC-CR; Figures 30-10, 30-12) are *very likely* to reduce the availability of associated fish and invertebrates that support many of the SSF in the tropics (*high confidence*). In the Pacific, the productivity of SSF on coral reefs has been projected to decrease by at least 20% by 2050 (Pratchett et al., 2011b), which is also *likely* to occur in other coral reef areas globally given the similar and growing stresses in these other regions (Table SM30-1; Section 30.5.4).

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 skipjack and yellowfin tuna resources by installing anchored fish-aggregating devices (FAD) close to shore (Bell et al., 2011b; 2013a,b; Table 30-2). These adaptation options and policies represent a "no regrets" strategy in that they provide benefits for coral reef fisheries and fishers irrespective of climate change and ocean acidification.

30.6.2.1.3. Northern Hemisphere HLSBS fisheries

The high-latitude fisheries in the Northern Hemisphere span from around 30/35°N to 60°N in the North Pacific and 80°N in the North Atlantic, covering a wide range of thermal habitats supporting subtropical/temperate species to boreal/arctic species. The characteristics of these

HLSBS environments, as well as warming trends, are outlined in Section 30.5.1 and Table 30-1. In part, as a result of 30 years of increase in temperature (Belkin, 2009; Sherman et al., 2009), there has been an increase in the size of fish stocks associated with high-latitude fisheries in the Northern Hemisphere. This is particularly the case for the Norwegian spring-spawning herring, which has recovered from near-extinction as a result of overfishing and a cooler climate during the 1960s (Toresen and Østvedt, 2000). The major components of both pelagic and demersal high-latitude fish stocks are boreal species located north of 50°N. Climate change is projected to increase high-latitude plankton production and displace zooplankton and fish species poleward. As a combined result of these future changes, the abundance of fish (particularly boreal species) may increase in the northernmost part of the high-latitude region (Cheung et al., 2011), although increases will only be moderate in some areas.

The changes in distribution and migration of pelagic fish shows considerable spatial and temporal variability, which can increase tensions among fishing nations. In this regard, tension over the Atlantic mackerel fisheries has led to what many consider the first climate change-related conflict between fishing nations (Cheung et al., 2012; Section 30.6.5), and which has emphasized the importance of developing international collaboration and frameworks for decision making (Miller et al., 2013; Sections 15.4.3.3, 30.6.7). The Atlantic mackerel has over the recent decades been a shared stock between the EU and Norway. However, the recent advancement of the Atlantic mackerel into the Icelandic EEZ during summer has resulted in Icelandic fishers operating outside the agreement between the EU and Norway. Earlier records of mackerel from the first half of the 20th and second half of the 19th century show, however, that mackerel was present in Icelandic waters during the earlier warm periods (Astthorsson et al., 2012). In the Barents Sea, the northeast Arctic cod, *Gadus morhua*, reached record-high abundance in 2012 and also reached its northernmost-recorded distribution (82°N) (ICES, 2012). A further northward migration is impossible as this would be into the Deep Sea Polar Basin, beyond the habitat of shelf species. A further advancement eastwards to the Siberian shelf is, however, possible. The northeast Arctic cod stock is shared exclusively by Norway and Russia, and to date there has been a good agreement between those two nations on the management of the stock. These examples highlight the importance of international agreements and cooperation (Table 30-4).

The HLSBS fisheries constitute a large-scale high-tech industry, with large investments in highly mobile fishing vessels, equipment, and land-based industries with capacity for adapting fisheries management and industries for climate change (Frontiers Economics, Ltd., 2013). Knowledge of how climate fluctuations and change affect the growth, recruitment, and distribution of fish stocks is presently not incorporated into fisheries management strategies (Perry et al., 2010). These strategies are vital for fisheries that hope to cope with the challenges of a changing ocean environment, and are centrally important to 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 through international treaties (Table 30-4) is a necessary adaptation 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 the time that stocks are in the various EEZs.

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 more than 255 million people. 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., 2012b; Section 10.6.1). Climate change, through impacts on ecosystems (e.g., coral reef bleaching), can reduce the appeal of destinations, increase operating costs, and/or increase uncertainty in a highly sensitive business environment (Scott et al., 2012b).

Several facets of the influence of climate change on the Ocean directly impact tourism (Section 10.6). Tourism is susceptible to extreme events such as violent storms, long periods of drought, and/or extreme precipitation events (Sections 5.4.3.4, 10.6.1; IPCC, 2012). SLR, through its influence on coastal erosion and submergence, salinization of water supplies, and changes to storm surge, increases the vulnerability of coastal tourism infrastructure, tourist safety, and iconic ecosystems (*high confidence*; Sections 5.3.3.2, 5.4.3.4, 10.6; Table SPM.1; IPCC, 2012). For example, approximately 29% of resorts in the Caribbean are within 1 m of the high tide mark and 60% are at risk of beach erosion from rapid SLR (Scott et al., 2012a).

Increasing sea temperatures (Section 30.3.1.1) can change attractiveness of locations and the opportunities for tourism through their influence on the movement of organisms and the state of ecosystems such as coral reefs (Section 10.6.2; Box CC-CR; UNWTO and UNEP, 2008). Mass coral bleaching and mortality (triggered by elevated sea temperatures; *high confidence*) can decrease the appeal of destinations for diving-related tourism, although the level of awareness of tourists of impacts (e.g., <50% of tourists were concerned about coral bleaching during a major bleaching year, 1998) and expected economic impacts have been found to be uncertain (Scott et al., 2012b). Some studies, however, have noted reduced tourist satisfaction and identified "dead coral" as one of the reasons for disappointment at the end of the holiday (Westmacott et al., 2000). 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 toward higher latitudes with climate change, or from summer to cooler seasons (Amelung et al., 2007; Section 10.6.1).

Options for adaptation by the marine tourism sector include (1) identifying and responding to inundation risks with current infrastructure, and planning for projected SLR when building new tourism infrastructure (Section 5.5; Scott et al., 2012a); (2) promoting shoreline stability and natural barriers by preserving ecosystems such as mangroves, salt marshes, and coral reefs (Section 5.5; Scott et al., 2012b); (3) deploying forecasting and early-warning systems in order to anticipate challenges to tourism and natural ecosystems (Strong et al., 2011; IPCC, 2012); (4) preparation of risk management and disaster preparation plans in order to respond to extreme events; (5) reducing the effect of other stressors on ecosystems and building resilience in iconic tourism features such as coral reefs and mangroves; and (6) educating tourists to improve understanding of the negative consequences of climate change over those stemming from local stresses (Scott et al., 2012a,b). Adaptation plans for tourism industries need to address specific operators and regions. For example, some operators may have costly infrastructure at risk while others may have few assets but are dependent on the integrity of natural environments and ecosystems (Turton et al., 2010).

30.6.2.3. Shipping

International shipping accounts for more than 80% of world trade by volume (UNCTAD, 2009a,b) and approximately 3% of global CO_2 emissions from fuel combustion although CO_2 emissions are expected to increase two- to threefold by 2050 (Heitmann and Khalilian, 2010; WGIII AR5 Section 8.1). Changes in shipping routes (Borgerson, 2008) and variation in the transport network due to shifts in grain production and global markets, as well as new fuel and weather-monitoring technology, may alter these emission patterns (WGIII AR5 Sections 8.3, 8.5). Extreme weather events, intensified by climate change, may interrupt ports and transport routes more frequently, damaging infrastructure and introducing additional dangers to ships, crews, and the environment (UNCTAD, 2009a,b; Pinnegar et al., 2012; Section 10.4.4). These issues have been assessed by some countries which have raised concerns over the potential for costly delays and cancellation of services, and the implications for insurance premiums as storminess and other factors increase risks (Thornes et al., 2012).

Climate change may benefit maritime transport by reducing Arctic sea ice and consequently shorten travel distances between key ports (Borgerson, 2008), thus also decreasing total GHG emissions from ships (WGIII AR5 Section 8.5.1). Currently, the low level of 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 issues), and a clear legal framework to address potential territorial claims that may arise, with a number of countries having direct interest in the Arctic. Further discussion of issues around melting Arctic sea ice and the Northern Sea Route are given in Chapter 28 (Sections 28.2.6, 28.3.4).

30.6.2.4. Offshore Energy and Mineral Resource Extraction and Supply

The marine oil and gas industry face potential impacts from climate change on its ocean-based activities. More than 100 oil and gas platforms were destroyed in the Gulf of Mexico by the unusually strong Hurricanes Katrina and Rita in 2005. Other consequences for oil pipelines and production facilities ultimately reduced US refining capacity by 20% (IPCC, 2012). The increasing demand for oil and gas has pushed operations to waters 2000 m deep or more, far beyond continental shelves. The very large-scale moored developments required 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 toward 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 scouring of the unconsolidated sediments by DS currents (Randolph et al., 2010). The influence of warming oceans on sea floor stability is widely debated due largely to uncertainties about the effects of methane and methane hydrates (Sultan et al., 2004; Archer et al., 2009; Geresi et al., 2009). Declining sea ice is also opening up the Arctic to further oil and gas extraction. Discussion of potential expansion of oil and mineral production in the Arctic is made in Chapter 28 (Sections 28.2.5-6, 28.3.4).

The principal threat to oil and gas extraction and infrastructure in maritime settings is the impact of extreme weather (Kessler et al., 2011), which is *likely* to increase given that future storm systems are expected to have greater energy (Emanuel, 2005; Trenberth and Shea, 2006; Knutson et al., 2010). Events such as Hurricane Katrina have illustrated challenges which will arise for this industry with projected increases in storm intensity (Cruz and Krausmann, 2008). In this regard, early warning systems and integrated planning offer some potential to reduce the effect of extreme events (IPCC, 2012).

30.6.3. Human Health

Major threats to public health due to climate change include diminished security of water and food supplies, extreme weather events, and changes in the distribution and severity of diseases, including those due to marine biotoxins (Costello et al., 2009; Sections 5.4.3.5, 6.4.2.3, 11.2). The predominantly negative impacts of disease for human communities are expected to be more serious in low-income areas such as Southeast Asia, southern and east Africa, and various sub-regions of South America (Patz et al., 2005), which also have under-resourced health systems (Costello et al., 2009). Many of the influences are directly or indirectly related to basin-scale changes in the Ocean (e.g., temperature, rainfall, plankton populations, SLR, and ocean circulation; McMichael et al., 2006). Climate change in the Ocean may influence the distribution of diseases such as cholera (Section 11.5.2.1), and the distribution and occurrence of HABs. The frequency of cholera outbreaks induced by *Vibrio cholerae* and other enteric pathogens are correlated with sea surface temperatures, multi-decadal fluctuations of ENSO, and plankton blooms, which may provide insight into how this disease may change with projected rates of ocean warming (Colwell, 1996; Pascual et al., 2000; Rodó et al., 2002; Patz et al., 2005; Myers and Patz, 2009; Baker-Austin et al., 2012). The incidence of diseases such as ciguatera also shows links to ENSO, with ciguatera becoming more prominent after periods of elevated sea temperature. This indicates that ciguatera may become more frequent in a warmer climate (Llewellyn, 2010), particularly given the higher prevalence of ciguatera in areas with degraded coral reefs (*low confidence*; Pratchett et al., 2011a).

30.6.4. Ocean-Based Mitigation

30.6.4.1. Deep Sea Carbon Sequestration

Carbon dioxide capture and storage into the deep sea and geologic structures are also discussed in WGIII AR5 Chapter 7 (Sections 7.5.5, 7.8.2, 7.12). The economic impact of deliberate CO_2 sequestration beneath the sea floor has previously been reviewed (IPCC, 2005). Active CO_2 sequestration from co-produced CO_2 into sub-sea geologic formations is being instigated in the North Sea and in the Santos Basin offshore from Brazil. These activities will increase as offshore oil and gas production increasingly exploits 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 DS organisms and ecosystems although chronic effects have not yet been studied. These risks are similar to those discussed previously with respect to ocean acidification and could further exacerbate declining O_2 levels and changing trophic networks in deep water areas (Seibel and Walsh, 2001; Section 6.4.2.2).

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. Annex 1 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. Offshore Renewable Energy

Renewable energy supply from the Ocean includes ocean energy and offshore wind turbines. The global technical potential for ocean and wind energy is not as high as solar energy although considerable potential still remains. Detailed discussion of the potential of renewable energy sources are given in WGIII AR5 Chapter 7 (Sections 7.4.2, 7.5.3, 7.8.2). There is an increasing trend in the renewable energy sector to offshore wind turbines (Section 10.2.2). At present, there is *high uncertainty* about how changes in wind intensity and patterns, and extreme events (from climate change), will impact the offshore wind energy sector. Given the design and engineering solutions available to combat climate change impacts (Tables 10-1, 10-7), it is *unlikely* that this sector will face insurmountable challenges from climate change.

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 citizens. These concerns have arisen as nation-states increasingly engage in operations ranging from humanitarian assistance in climate-related disasters to territorial issues exacerbated by changing coastlines, human communities, resource access, and new seaways (Kaye, 2012; Rahman, 2012; Section 12.6). 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 EEZ 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; IUU fishing; and human, arms, and drug trafficking (Kaye, 2012). While the linkages have not been clearly defined in all cases, it is possible that changes in the Ocean as result of climate change will increase pressure on resources aimed at maintaining maritime security and countering criminal activity, disaster relief operations, and freedom of navigation (Section 12.6.2). National maritime security capacity and infrastructure may also require rethinking as new challenges present themselves as a result of climate change and ocean acidification (Allen and Bergin, 2009; Rahman, 2012; Sections 12.6.1-2).

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 (Section 28.2.6). Conversely, such new features may also lead to increasing international tensions as States perceive new vulnerabilities from these changes to geography.

Like commercial shipping (Section 30.6.2.3), naval operations in many countries result in significant GHG emissions (e.g., the US Navy emits around 2% of the national GHG emissions; Mabus, 2010). As a result, there are a number of programs being implemented by navies around the world to try and reduce their carbon footprint and air pollution such as improving engine efficiency, reducing fouling of vessels, increasing the use of biofuels, and using nuclear technology for power generation, among other initiatives.

30.7. Synthesis and Conclusions

Evidence that human activities are fundamentally changing the Ocean is *virtually certain*. Sea temperatures have increased rapidly over the past 60 years at the same time as pH has declined, consistent with the expected influence of rising atmospheric concentrations of CO_2 and other GHGs (*very high confidence*). The rapid rate at which these fundamental physical and chemical parameters of the Ocean are changing is unprecedented within the last 65 Ma (*high confidence*) and possibly 300 Ma (*medium confidence*). As the heat content of the Ocean has increased, the Ocean has become more stratified (*very likely*), although there is considerable regional variability. In some cases, changing surface wind has influenced the extent of mixing and upwelling, although our understanding of where and why these differences occur regionally is uncertain. The changing structure and function of the Ocean has led to changes in parameters such as O_2, carbonate ion, and inorganic nutrient concentrations (*high confidence*). Not surprisingly, these fundamental changes have resulted in responses by key marine organisms, ecosystems, and ecological processes, with negative implications for hundreds of millions of people that depend on the ecosystem goods and services provided (*very likely*). Marine organisms are migrating at rapid rates toward higher latitudes, fisheries are transforming, and many organisms are shifting their reproductive and migratory activity in time and in concert with changes in temperature and other parameters. Ecosystems such as coral reefs are declining rapidly (*high confidence*). An extensive discussion of these changes is provided in previous sections and in other chapters of AR5.

Table 30-3 | Key risks to ocean and coastal issues from climate change and the potential for risk reduction through mitigation and adaptation. Key risks are identified based on assessment of the literature and expert judgments made by authors of the various WGII AR5 chapters, with supporting evaluation of evidence and agreement in the referenced chapter sections. Each key risk is characterized as very low, low, medium, high, or very high. Risk levels are presented for the near-term era of committed climate change (here, for 2030–2040), in which projected levels of global mean temperature increase do not diverge substantially across emissions scenarios. Risk levels are also presented for the longer term era of climate options (here, for 2080–2100), for global mean temperature increases of 2°C and 4°C above pre-industrial levels. For each time frame, risk levels are estimated for the current state of adaptation and for a hypothetical highly adapted state. As the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks. Relevant climate variables are indicated by symbols.

Climate-related drivers of impacts								Level of risk & potential for adaptation
Warming trend	Extreme temperature	Extreme precipitation	Precipitation	Damaging cyclone	Sea level	Ocean acidification	Hypoxia	Potential for additional adaptation to reduce risk; Risk level with **high** adaptation; Risk level with **current** adaptation

Risks to ecosystems and adaptation options

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Changes in ecosystem productivity associated with the redistribution and loss of net primary productivity in open oceans. (*medium confidence*) [6.5.1, 6.3.4, Box CC-PP]	Adaptation options are limited to the translocation of industrial fishing activities due to regional decreases (low latitude) versus increases (high latitude) in productivity, or to the expansion of aquaculture.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high
Distributional shift in fish and invertebrate species, fall in fisheries catch potential at low latitudes, e.g., in EUS, CBS, and STG regions. (*high confidence*) [6.3.1, Box CC-MB]	Evolutionary adaptation potential of fish and invertebrate species to warming is limited as indicated by their changes in distribution to maintain temperatures. Human adaptation options involve the large-scale translocation of industrial fishing activities following the regional decreases (low latitude) versus (possibly transient) increases (high latitude) in catch potential as well as deploying flexible management that can react to variability and change. Further options include improving fish resilience to thermal stress by reducing other stressors such as pollution and eutrophication, the expansion of sustainable aquaculture and development of alternative livelihoods in some regions.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high
High mortalities and loss of habitat to larger fauna including commercial species due to hypoxia expansion and effects. (*high confidence*) [6.3.3, 30.5.3.2, 30.5.4.1-2]	Human adaptation options involve the large-scale translocation of industrial fishing activities as a consequence of the hypoxia-induced decreases in biodiversity and fisheries catch of pelagic fish and squid. Special fisheries may benefit (Humboldt squid). Reducing the amount of organic carbon running off of coastlines by controlling nutrients and pollution running off agricultural areas can reduce microbial activity and consequently limit the extent of the oxygen drawdown and the formation of coastal dead zones.	O_2	Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high
Ocean acidification: Reduced growth and survival of commercially valuable shellfish and other calcifiers, e.g., reef building corals, calcareous red algae. (*high confidence*) [5.3.3.5, 6.1.1, 6.3.2, 6.4.1.1, 30.3.2.2, Box CC-OA]	Evidence for differential resistance and evolutionary adaptation of some species exists but is likely limited by the CO_2 concentrations and high temperatures reached; adaptation options shifting to exploit more resilient species or the protection of habitats with low natural CO_2 levels, as well as the reduction of other stresses, mainly pollution and limiting pressures from tourism and fishing.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high
Reduced biodiversity, fisheries abundance and coastal protection by coral reefs due to heat-induced mass coral bleaching and mortality increases, exacerbated by ocean acidification, e.g., in CBS, SES, and STG regions. (*high confidence*) [5.4.2.4, 6.4.2, 30.3.1.1, 30.3.2.2, 30.5.2, 30.5.3, 30.5.4, 30.5.6, Box CC-CR]	Evidence of rapid evolution by corals is very limited or nonexistent. Some corals may migrate to higher latitudes. However, the movement of entire reef systems is unlikely given estimates that they need to move at the speed of 10 – 20 km yr^{-1} to keep up with the pace of climate change. Human adaptation options are limited to reducing other stresses, mainly enhancing water quality and limiting pressures from tourism and fishing. This option will delay the impacts of climate change by a few decades but is likely to disappear as thermal stress increases.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high
Coastal inundation and habitat loss due to sea level rise, extreme events, changes in precipitation, and reduced ecological resilience, e.g., in CBS and STG subregions. (*medium to high confidence*) [5.5.2, 5.5.4, 30.5.6.1.3, 30.6.2.2, Box CC-CR]	Options to maintain ecosystem integrity are limited to the reduction of other stresses, mainly pollution and limiting pressures from tourism, fishing, physical destruction, and unsustainable aquaculture. Reducing deforestation and increasing reforestation of river catchments and coastal areas to retain sediments and nutrients. Increased mangrove, coral reef, and seagrass protection and restoration to protect numerous ecosystem goods and services such as coastal protection, tourist value, and fish habitat.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high
Marine biodiversity loss with high rate of climate change. (*medium confidence*) [6.3.1-3, 6.4.1.2-3, Table 30.4, Box CC-MB]	Adaptation options are limited to the reduction of other stresses, mainly to reducing pollution and to limiting pressures from tourism and fishing.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high

Continued next page →

Table 30-3 (continued)

Risks to fisheries				
Key risk	**Adaptation issues & prospects**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation** (Very low / Medium / Very high)
Decreased production of global shellfish fisheries. (*high confidence*) [6.3.2, 6.3.5, 6.4.1.1, 30.5.5, 30.6.2.1, Box CC-OA]	Effective shift to alternative livelihoods, changes in food consumption patterns, and adjustment of (global) markets.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Global redistribution and decrease of low-latitude fisheries yields are paralleled by a global trend to catches having smaller fishes. (*medium confidence*) [6.3.1, 6.4.1, 6.5.3, 30.5.4, 30.5.6, 30.6.2]	Increasing coastal poverty at low latitudes as fisheries becomes smaller – partially compensated by the growth of aquaculture and marine spatial planning, as well as enhanced industrialized fishing efforts.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Redistribution of catch potential of large pelagic-highly migratory fish resources, such as tropical Pacific tuna fisheries. (*high confidence*) [6.3.1, 6.4.3, Table 30.4]	International fisheries agreements and instruments, such as the tuna commissions, may have limited success in establishing sustainable fisheries yields.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Variability of small pelagic fishes in EBUEs is becoming more extreme at interannual to multidecadal scales, making industry and management decisions more uncertain. (*medium confidence*) [6.3.2, 6.3.3, 30.5.2, 30.5.5, Box CC-UP]	Development of new and specific management tools and models may have limited success to sustain yields. Reduction in fishing intensity increases resilience of the fisheries.	O_2	Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Decrease in catch and species diversity of fisheries in tropical coral reefs, exacerbated by interactions with other human drivers such as eutrophication and habitat destruction. (*high confidence*) [6.4.1, 30.5.3-4, 30.5.6, Box CC-CR]	Restoration of overexploited fisheries and reduction of other stressors on coral reefs delay ecosystem changes. Human adaptation includes the usage of alternative livelihoods and food sources (e.g., coastal aquaculture).		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Current spatial management units, especially the marine protected areas (MPAs), may fail in the future due to shifts in species distributions and community structure. (*high confidence*) [6.3.1, 6.4.2.1, 30.5.1, Box CC-MB]	Continuous revision and shifts of MPA borders, and of MPA goals and performance.	O_2	Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	

Continued next page →

30.7.1. Key Risks and Vulnerabilities

The rapid changes in the physical, chemical, and biological state of the Ocean pose a number of key risks and vulnerabilities for ecosystems, communities, and nations worldwide. Table 30-3 and Figure 30-12 summarize risks and vulnerabilities from climate change and ocean acidification, along with adaptation issues and prospects, and a summary of expert opinion on how these risks will change under further changes in environmental conditions.

Rising ocean temperatures are changing the distribution, abundance, and phenology of many marine species and ecosystems, and consequently represent a key risk to food resources, coastal livelihoods, and industries such as tourism and fishing, especially for HLSBS, CBS, STG, and EBUE (Sections 6.3.1, 6.3.4, 7.3.2.4, 30.5; Figure 30-12; Table 30-3; Box CC-MB). Key risks involve changes in the distribution and abundance of key fishery species (*high confidence*; Section 30.6.2.1; Figure 30-12 A,B,G,H) as well as the spread of disease and invading organisms, each of which has the potential to impact ecosystems as well as aquaculture and fishing (Sections 6.3.5, 6.4.1.1, 6.5.3, 7.3.2.4, 7.4.2, 29.5.3-4; Table 30-3). Adaptation to these changes may be possible in the short-term through dynamic fisheries policy and management (i.e., relocation of fishing effort; Table 30-3), as well as monitoring and responding to potential invading species in coastal settings. The increasing frequency of thermal extremes (Box CC-HS) will also increase the risk that the thermal threshold of corals and other organisms is exceeded on a more frequent

Table 30-3 (continued)

Risks to humans and infrastructure (continued)				
Key risk	**Adaptation issues & prospects**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation**
Reduced coastal socioeconomic security. (*high confidence*) [5.5.2, 5.5.4, 30.6.5, 30.7.1]	Human adaptation options involve (1) protection using coastal defences (e.g. seawalls where appropriate and economic) and soft measures (e.g., mangrove replanting and enhancing coral growth); (2) accommodation to allow continued occupation of coastal areas by making changes to human activities and infrastructure; and (3) managed retreat as a last viable option. Vary from large-scale engineering works to smaller scale community projects. Options are available under the more traditional CZM (coastal zone management) framework but increasingly under DRR (disaster risk reduction) and CCA (climate change adaptation) frameworks.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high *
				***High confidence* in existence of adaptation measures, *Low confidence* in magnitude of risk reduction
Reduced livelihoods and increased poverty. (*medium confidence*) [6.4.1-2, 30.6.2, 30.6.5]	Human adaptation options involve the large-scale translocation of industrial fishing activities following the regional decreases (low latitude) versus increases (high latitude) in catch potential and shifts in biodiversity. Artisanal fisheries are extremely limited in their adaptation options by available financial resources and technical capacities, except for their potential shift to other species of interest.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Impacts due to increased frequency of harmful algal blooms (*medium confidence*) [6.4.2.3]	Adaptation options include improved monitoring and early warning system, reduction of stresses favoring harmful algal blooms, mainly pollution and eutrophication, as well as the avoidance of contaminated areas and fisheries products.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Impacts on marine resources threatening regional security as territorial disputes and food security challenges increase (*limited evidence, medium agreement*) [IPCC 2012, 30.6.5, 12.4-12.6, 29.3]	Decrease in marine resources, movements of fish stocks and opening of new seaways , and impacts of extreme events coupled with increasing populations will increase the potential for conflict in some regions, drive potential migration of people, and increase humanitarian crises.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high
Impacts on shipping and infrastructure for energy and mineral extraction increases as storm intensity and wave height increase in some regions (e.g., high latitudes) (*high confidence*) [IPCC 2012, 30.6.5, 12.4-12.6, 29.3]	Adaptation options are to limit activities to particular times of the year and/or develop strategies to decrease the vulnerability of structures and operations.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low – Medium – Very high

CBS = Coastal Boundary Systems; EBUE = Eastern Boundary Upwehlling Ecosystems; EUS = Equatorial Upwelling Systems; HLSBS = High-Latitude Spring Bloom Systems; SES = Semi-Enclosed Seas; STG = Subtropical Gyres.

basis (especially in CBS, STG, SES, HLSBS, and EUS regions; Sections 6.2, 30.5; Box CC-CR). These changes pose a key risk to vulnerable ecosystems such as mangroves and coral reefs, with potential to have a series of serious impacts on fisheries, tourism, and coastal ecosystem services such as coastal protection (Sections 5.4.2.4, 6.3.2, 6.3.5, 6.4.1.3, 7.2.1.2, 29.3.1.2, 30.5; Table 30-3; Box CC-CR). Genetic adaptation of species to increasing levels of stress may not occur fast enough given fairly long generation times of organisms such as reef-building corals and many other invertebrates and fish (Table 30-3). In this case, risks may be reduced by addressing stresses not related to climate change (e.g., pollution, overfishing), although this strategy could have minimal impact if further increases in sea temperature occur (*high confidence*).

Loss of these important coastal ecosystems is associated with emerging risks associated with the collapse of some coastal fisheries along with livelihoods, food, and regional security (*medium confidence*). These changes are *likely* to be exacerbated by other key risks such as coastal inundation and habitat loss due to SLR, as well as intensified precipitation events (*high confidence*; Section 5.4; Box CC-CR). Adaptation options in this case include engineered coastal defenses, reestablishing coastal vegetation such as mangroves, protecting water supplies from salination, and developing strategies for coastal communities to withdraw to less vulnerable locations over time (Section 5.5).

The recent decline in O_2 concentrations has been ascribed to warming through the effect on ocean mixing and ventilation, as well as the solubility of O_2 and its consumption by marine microbes (Sections 6.1.1.3, 6.3.3, 30.3.2.3, 30.5.7). This represents a key risk to ocean ecosystems (*medium confidence*; Figure 30-12 5,6,C). These changes increase the vulnerability of marine communities, especially those below the euphotic zone, to hypoxia and ultimately lead to a restriction of suitable habitat (*high confidence*; Figure 30-12 5). In the more extreme case, often exacerbated by the contribution of organic carbon from land-based sources, "dead zones" may form. Decreasing oxygen, consequently, is *very likely* to increase the vulnerability of fisheries and aquaculture (*medium confidence*; Figure 30-12 C), and consequently puts livelihoods at risk, particularly in EBUE (e.g., California and Humboldt Current ecosystems; Section 30.5.5), SES (e.g., Baltic and Black Seas; Section 30.5.3), and CBS (e.g., Gulf of Mexico, northeast Indian Ocean; Sections 30.3.2.3, 30.5.4). It is *very likely* that the warming of surface waters has also increased the stratification of the upper ocean by about 4% between 0 and 200 m from 1971 to 2010 in all oceans north of about 40°S. In many cases, there is significant adaptation opportunity to reduce hypoxia locally by reducing the flow of organic carbon, hence microbial activity, within these coastal systems (Section 30.5.4). Relocating fishing effort, and modifying procedures associated with industries such as aquaculture, may offer some opportunity to adapt to these changes (*likely*). Declining O_2 concentrations are *likely* to have significant impacts on DS habitats, where organisms are relatively sensitive to environmental changes of this nature owing to the very constant conditions under which they have evolved (Section 30.5.7).

Ocean acidification has increased the vulnerability of ocean ecosystems by affecting key aspects of the physiology and ecology of marine organisms (particularly in CBS, STG, and SES; Section 6.3.2; Table 30-3; Box CC-OA). Decreasing pH and carbonate ion concentrations reduce the ability of marine organisms to produce shells and skeletons, and may interfere with a range of biological processes such as reproduction, gas exchange, metabolism, navigation ability, and neural function in a broad range of marine organisms that show minor to major influences of ocean acidification on their biology (Sections 6.3.2, 30.3.2.2; Box CC-OA). Natural variability in ocean pH can interact with ocean acidification to create damaging periods of extremes (i.e., high CO_2, low O_2 and pH), which can have a strong effect on coastal activities such as aquaculture (*medium confidence*; Section 6.2; Figure 30-12 A; Box CC-UP). There may be opportunity to adapt aquaculture to increasingly acidic conditions by monitoring natural variability and restricting water intake to periods of optimal conditions. Reducing other non-climate change or ocean acidification associated stresses also represents an opportunity to build greater ecological resilience against the impacts of changing ocean carbonate chemistry. Ocean acidification is also an emerging risk for DS habitats as CO_2 continues to penetrate the Ocean, although the impacts and adaptation options are poorly understood and explored. Ocean acidification has heightened importance for some groups of organisms and ecosystems (Box CC-OA). In ecosystems that are heavily dependent on the accumulation of calcium carbonate over time (e.g., coral reefs, *Halimeda* beds), increasing ocean acidification puts at risk ecosystems services that are critical for hundreds of thousands of marine species, plus people and industries, particularly within CBS, STG, and SES (*high confidence*). Further risks may emerge from the non-linear interaction of different factors (e.g., increasing ocean temperature may amplify effects of ocean acidification, and vice versa) and via the interaction of local stressors with climate change (e.g., interacting changes may lead to greater ecosystems disturbances than each impact on its own). There is an urgent need to understand these types of interactions and impacts, especially given the long time it will take to return ocean ecosystems to preindustrial pH and carbonate chemistry (i.e., tens of thousands of years (FAQ 30.1) should CO_2 emissions continue at the current rate).

It is *very likely* that surface warming has increased stratification of the upper ocean, contributing to the decrease in O_2 along with the temperature-related decreases in oxygen solubility (WGI AR5 Section 3.8.3). Changes to wind speed, wave height, and storm intensity influence the location and rate of mixing within the upper layers of the Ocean and hence the concentration of inorganic nutrients (e.g., in EBUE, EUS; Figure 30-12 1,3). These changes to ocean structure increase the risks and vulnerability of food webs within the Ocean. However, our understanding of how primary productivity is going to change in a warming and more acidified ocean is limited, as is our understanding of how upwelling will respond to changing surface wind as the world continues to warm (Boxes CC-PP, CC-UP). As already discussed, these types of changes can have implications for the supply of O_2 into the Ocean and the upward transport of inorganic nutrients to the euphotic zone. Although our understanding is limited, there is significant potential for regional increases in wind speed to result in greater rates of upwelling and the supply of inorganic nutrients to the photic zone. Although this may increase productivity of phytoplankton communities and associated fisheries, greater rates of upwelling can increase the risk of hypoxic conditions developing at depth as excess primary production sinks into the Ocean and stimulates microbial activity at depth (Sections 6.1.1.3, 30.3.2.3, 30.5.5; Table 30-3). Changes in storm intensity may increase the risk of damage to shipping and industrial infrastructure, which increases the risk of accidents and delays to the transport of products between countries, security operations, and the extraction of minerals from coastal and oceanic areas (Section 30.6.2; IPCC, 2012).

Frequently Asked Questions

FAQ 30.5 | How can we use non-climate factors to manage climate change impacts on the oceans?

The Ocean is exposed to a range of stresses that may or may not be related to climate change. Human activities can result in pollution, eutrophication (too many nutrients), habitat destruction, invasive species, destructive fishing, and over-exploitation of marine resources. Sometimes, these activities can increase the impacts of climate change, although they can, in a few circumstances, dampen the effects as well. Understanding how these factors interact with climate change and ocean acidification is important in its own right. However, reducing the impact of these non-climate factors may reduce the overall rate of change within ocean ecosystems. Building ecological resilience through ecosystem-based approaches to the management of the marine environment, for example, may pay dividends in terms of reducing and delaying the effects of climate change (*high confidence*).

The proliferation of key risks and vulnerabilities to the goods and services provided by ocean ecosystems as a result of ocean warming and acidification generate a number of key risks for the citizens of almost every nation. Risks to food security and livelihoods are expected to increase over time, aggravating poverty and inequity (Table 30-3). As these problems increase, regional security is likely to deteriorate as disputes over resources increase, along with increasing insecurity of food and nutrition (Sections 12.4-6, 29.3.3, 30.6.5; Table 30-3; IPCC, 2012).

30.7.2. Global Frameworks for Decision Making

Global frameworks for decision making are central to management of vulnerability and risk at the scale and complexity of the world's oceans. General frameworks and conventions for policy development and decision making within oceanic and coastal regions are important in terms of the management of stressors not directly due to ocean warming or acidification, but that may influence the outcome of these two factors. Tables 30-3 and 30-4 outline a further set of challenges arising from multiple interacting stressors, as well as potential risks and vulnerabilities, ramifications, and adaptation options. In the latter case, examples of potential global frameworks and initiatives for beginning and managing these adaptation options are described. These frameworks 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).

The United Nations Convention on the Law of the Sea (UNCLOS) 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

Table 30-4 | Ramifications, adaptation options, and frameworks for decision making for ocean regions. Symbols for primary drivers: IC = ice cover; NU = nutrient concentration; OA = ocean acidification; SLR = sea level rise; SS = storm strength; T = sea temperature (↑ = increased; ↓ = decreased; * = uncertain).

Primary driver(s)	Biophysical change projected	Key risks and vulnerabilities	Ramifications	Adaptation options	Policy frameworks and initiatives (examples)	Key references and chapter sections
↑T, ↑OA	Spatial and temporal variation in primary productivity (*medium confidence* at global scales; Box CC-PP)	Reduced fisheries production impacts important sources of income to some countries while others may see increased productivity (e.g., as tuna stocks shift eastwards in the Pacific) (*medium confidence*).	Reduced national income, increased unemployment, plus increase in poverty. Potential increase in disputes over national ownership of key fishery resources (*likely*)	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" provides social and economic incentives to fisheries and fishers for adaptation.	UNCLOS, PEMSEA, CTI, RFMO agreements, UNSFSA	Bell et al. (2011, 2013a); Tsamenyi and Hanich (2012); Sections 6.4.1, 6.5.3, 30.6.2.1, 30.7.2; Box CC-PP
↑T, ↑OA	Ecosystem regime shifts (e.g., coral to algal reefs; structural shifts in phytoplankton communities) (*medium confidence*)	Reduced fisheries production of coastal habitats and ecosystems such as coral reefs (*medium confidence*).	Decreased food and employment security and human migration away from coastal zone (*likely*)	Strengthen coastal zone management to reduce contributing stressors (e.g., coastal pollution, over-harvesting, and physical damage to coastal resources). Promote Blue Carbon[a] initiatives.	PEMSEA, CTI, PACC, MARPOL, UNHCR, CBD, International Organization for Migration, Global Environment Facility, International Labor Organization	Bell et al. (2013a); Sections 5.4.3, 6.3.1–2, 12.4, 29.3.1, 29.3.3, 30.5.2–4, 30.5.6, 30.6.1, 30.6.2.1; Box CC-CR
		Tourist appeal of coastal assets decreases as ecosystems change to less "desirable" state, reducing income to some countries (*low confidence*).	Increased levels of coastal poverty in some countries as tourist income decreases (*likely*)	As above, strengthen coastal zone management and reduce additional stressors on tourist sites; implement education programs and awareness among visitors. Diversify tourism activities.	CBD, PEMSEA, CTI, PACC, UNHCR, MARPOL	Kenchington and Warner (2012); Sections 5.5.4.1, 6.4.1–2, 10.6, 30.6.2.2
		Increased risk of some diseases (e.g., ciguatera, harmful algal blooms) as temperatures increase shift and ecosystems shift away from coral dominance (*low confidence*).	Increased disease and mortality; decreases in coastal food resources and fisheries income (*likely*)	Increase monitoring and education surrounding key risks (e.g., ciguatera); develop alternate fisheries and income for periods when disease incidence increases, and develop or update health response plans.	National policy strategies and regional cooperation needed	Llewellyn (2010); Sections 6.4.2.3, 10.6, 29.3.3.2, 29.5.3, 30.6.3
		Increased poverty and dislocation of coastal people (particularly in the tropics) as coastal resources such as fisheries degrade (*medium confidence*)	Increased population pressure on migration destinations (e.g., large regional cities), and reduced freedom to navigate in some areas (as criminal activity increases) (*likely*)	Develop alternative industries and income for affected coastal people. Strengthen coastal security both nationally and across regions. Increase cooperation over handling of criminal activities.	UNCLOS, PEMSEA, CTI, International Ship and Port Facility Security, IMO, Bali Process, Association of Southeast Asian Nations MLA Treaty and bilateral extradition and MLA agreements	Kaye (2012); Rahman (2012); Sections 12.4–6,29.3.3, 29.6.2, 30.6.5

Continued next page →

[a]Blue Carbon initiatives include conservation and restoration of mangroves, saltmarsh, and seagrass beds as carbon sinks (Section 30.6.1).

Notes: CBD = Convention on Biological Diversity; CTI = Coral Triangle Initiative; IHO = International Hydrographic Organization; IOM = International Organization of Migration; ISPS = International Ship and Port Facility Security; MARPOL = International Convention for the Prevention of Pollution From Ships; MLA = mutual legal assistance; PACC = Pacific Adaptation to Climate Change Project; PEMSEA = Partnerships in Environmental Management for the Seas of East Asia; RFMO = Regional Fisheries Management Organizations; UNCLOS = United Nations Convention on the Law of the Sea; UNHCR = United Nations High Commissioner for Refugees; UNSFSA = United Nations Straddling Fish Stocks Agreement.

Table 30-4 (continued)

Primary driver(s)	Biophysical change projected	Key risks and vulnerabilities	Ramifications	Adaptation options	Policy frameworks and initiatives (examples)	Key references and chapter sections
↑T	Migration of organisms and ecosystems to higher latitudes (*high confidence*)	Reorganization of commercial fish stocks and ecological regime shifts (*medium to high confidence*)	Social and economic disruption (*very likely*)	Increase international cooperation and improve understanding of regime changes; implement early-detection monitoring of physical and biological variables and regional seasonal forecasting; include related uncertainties into fisheries management; provide social and economic incentives for industry.	UNCLOS, CBD, RFMO agreements, UNSFSA	Sections 7.4.2, 6.5, 30.5, 30.6.2.1; Box CC-MB
		Increase in abundance, growing season, and distributional extent of pests and fouling species (*medium confidence*)	Increased disease risk to aquaculture and fisheries. Income loss and increased operating and maintenance costs (*very likely*)	Increase environmental monitoring; promote technological advances to deal with pest and fouling organisms; increase vigilance and control related to biosecurity.	IMO, ballast water management, Anti- Fouling Convention	Sections 6.4.1.5, 7.3.2.4, 29.5.3–4, 30.6.2.1; Box CC-MB
		Threats to human health increase due to expansion of pathogen distribution to higher latitudes (*low confidence*)	Increased disease and mortality in some coastal communities (*likely*)	Reduce exposure through increased monitoring and education, adoption, or update of health response plans to outbreaks.	UNICEF, World Health Ogranization, IHOs, and national governments	Myers and Patz (2009); Sections 6.4.3, 10.8.2, 11.7, 29.3.3, 30.6.3; Box CC-MB
↑T, ↑NU, ↑OA*	Increased incidence of harmful algal blooms (*low confidence*)	Increased threats to ecosystems, fisheries, and human health (*medium confidence*)	Reduced supply of marine fish and shellfish and greater incidence of disease among some coastal communities (*likely*)	Provide early-detection monitoring and improve predictive models; provide education and adoption or update of health response plans.	CTI, PEMSEA, World Health Organization, MARPOL	Llewellyn (2010);, Sections 30.6.3, 11.7, 6.4.2.3
↑T	Increased precipitation as a result of intensified hydrological cycle in some coastal areas (*medium confidence*)	Increased freshwater, sediment, and nutrient flow into coastal areas; increase in number and severity of flood events (*medium to high confidence*)	Increasing damage to coastal reef systems with ecological regime shifts in many cases (*very likely*)	Improve management of catchment and coastal processes; expand riparian vegetation along creeks and rivers; improve agricultural retention of soils and nutrients.	CTI, PEMSEA, Secretariat of the Pacific Regional Environment Programme	Sections 3.4, 29.3.1, 30.5.4, 30.6.1
↑T	Changing weather patterns, storm frequency (*medium confidence*)	Increased risk of damage to infrastructure such as that involved in shipping and oil and gas exploration and extraction (*medium to low confidence*)	Increased damage and associated costs (*likely*)	Adjust infrastructure specifications, develop early-warning systems, and update emergency response plans to extreme events.	IMO	IPCC (2012); Sections 10.4.4, 29.3, 30.6.2.3–4
↑SLR, ↑SS	Increased wave exposure of coastal areas and increased sea level (*high confidence*)	Exposure of coastal infrastructure and communities to damage and inundation, increased coastal erosion (*high confidence*)	Increased costs to human towns and settlements, numbers of displaced people, and human migration (*very likely*)	Develop integrated coastal management that considers SLR in planning and decision making; increase understanding of the issues through education.	UNICEF, IHOs, and national governments	Warner (2012); Sections 5.5, 12.4.1, 29.5.1, 30.3.1.2, 30.6.5
		Inundation of coastal aquifers reduces water supplies and decreases coastal agricultural productivity (*high confidence*).	Reduced food and water security leads to increased coastal poverty, reduced food security, and migration (*very likely*).	Assist communities in finding alternatives for food and water, or assist in relocation of populations and agriculture from vulnerable areas.	UNICEF, IHOs, and national governments.	Warner (2012); Sections 5.4.3, 12.4.1, 29.3.2, 30.3.1.2
↑SLR	Risk of inundation and coastal erosion, especially in low-lying countries (*high confidence*)	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 (*high confidence*).	Lack of clarity increases, as do disputes over maritime limits and maritime jurisdiction. Some nations at risk of major losses to their territorial waters (*very likely*)	Seek resolution of "shifting national baselines" issue (retreat and redefinition, stabilization, or fixation of exclusive economic zones and other currently defined maritime jurisdiction limits).	UNCLOS	IPCC (2012); Schofield and Arsana (2012); Warner and Schofield (2012); Sections 5.5, 30.6.5
↑T, ↓IC	Loss of summer sea ice (*high confidence*)	Access to northern coasts of Canada, USA, and Russia increases security concerns (*high confidence*).	Potential for increased tension on different interpretations of access rights and boundaries (*likely to very likely*)	Seek early resolution of areas in dispute currently and in the future.	UNCLOS	Chapter 28
		New resources become available as ice retreats, increasing vulnerability of international borders in some cases (*medium confidence*).	Tensions over maritime claims and ownership of resources (*likely*)	Sort out international agreements.		

Convention. UNCLOS replaced earlier frameworks that were built around the "freedom of the seas" concept and that limited territorial rights to 3 nm off a coastline. UNCLOS 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 seabed beyond national jurisdiction. The relationship between climate change and UNCLOS is not clear and depends on interpretation of key elements within the UNFCCC (United Nations Framework Convention for Climate Change) and Kyoto Protocol (Boyle, 2012). However, UNCLOS provides mechanisms to help structural 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 Ocean.

There are many existing international conventions and agreements that explicitly recognize climate change (Table 30-4). The UN Straddling Fish Stocks Agreement (UNSFSA) aims at enhancing international cooperation of fisheries resources, with an explicit understanding under Article 6 that management needs to take account "existing and predicted oceanic, environmental and socio-economic conditions" and to undertake "relevant research, including surveys of abundance, biomass surveys, hydro-acoustic surveys, research on environmental factors affecting stock abundance, and oceanographic and ecological studies" (UNSFSA, Annex 1, Article 3). International conventions such as these will become increasingly important as changes to the distribution and abundance of fisheries are modified by climate change and ocean acidification.

Global frameworks for decision making are increasingly important in the case of the Ocean, most of which falls outside national boundaries (Oude Elferink, 2012; Warner, 2012). Approximately 64% of the Ocean (40% of the Earth's surface) is outside EEZs and continental shelves of the world's nations (high seas and seabed beyond national jurisdiction). With rapidly increasing levels of exploitation, there are increasing calls for more effective decision frameworks aimed at regulating fishing and other activities (e.g., bio-prospecting) within these ocean "commons." These international frameworks will become increasingly valuable as nations respond to impacts on fisheries resources that stretch across national boundaries. One such example is the multilateral cooperation that was driven by President Yudhoyono of Indonesia in August 2007 and 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 132,800 km of coastline) cooperation between the governments of Indonesia, Philippines, Malaysia, Papua New Guinea, the 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). Partnerships, such as CTI, 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.

An initiative called the Global Partnership for Oceans set out to establish a global framework with which to share experience, resources, and expertise, as well as to engage governments, industry, civil, and public sector interests in both understanding and finding solutions to key issues such as overfishing, pollution, and habitat destruction (Hoegh-Guldberg et al., 2013). 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 Ocean.

Global partnerships are also essential for providing support to the 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 negative consequences of climate change and ocean acidification on the world's ocean and coastal resources.

30.7.3. Emerging Issues, Data Gaps, and Research Needs

Although there has been an increase in the number of studies being undertaken to understand the physical, chemical, and biological changes within the Ocean in response to climate change and ocean acidification, the number of marine studies of ecological impacts and risks still lag behind terrestrial studies (Hoegh-Guldberg and Bruno, 2010; Poloczanska et al., 2013). Rectifying this gap should be a major international objective given the importance of the Ocean in terms of understanding and responding to future changes and consequences of ocean warming and acidification.

30.7.3.1. Changing Variability and Marine Impacts

Understanding the long-term variability of the Ocean is critically important in terms of the detection and attribution of changes to climate change (Sections 30.3, 30.5.8), but also in terms of the interaction between variability and anthropogenic climate change. Developing instrument systems that expand the spatial and temporal coverage of the Ocean and key processes will be critical to documenting and understanding its behavior under further increases in average global temperature and changes in the atmospheric concentration of CO_2. International collaborations such as the Argo network of oceanographic floats illustrate how international cooperation can rapidly improve our understanding of the physical behavior of the Ocean and will provide important insight into its long-term subsurface variability (Schofield et al., 2013).

30.7.3.2. Surface Wind, Storms, and Upwelling

Improving our understanding of the potential behavior of surface wind in a warming world is centrally important to our understanding of how upwelling will change in key regions (e.g., EUS, EBUE; Box CC-UP). Understanding these changes will provide important information for future fisheries management but will also illuminate the potential risks of intensified upwelling leading to hypoxia at depth and the potential expansion of "dead zones" (Sections 30.3.2, 30.5.2-4). Understanding surface wind in a warming climate will also yield important information on surface mixing as well as how surface wave height might also vary, improving our understanding of potential interactions in coastal areas between wind, waves, and SLR (Section 30.3.1). Given the importance of mixing and upwelling to the supply of inorganic nutrients to the surface layers of the ocean, understanding these important phenomena at the ocean-atmosphere interface will provide important insight into how ocean warming and acidification are likely to impact ecosystems, food webs, and ultimately important fisheries such as those found along the west coasts of Africa and the Americas.

30.7.3.3. Declining Oxygen Concentrations

The declining level of O_2 in the Ocean is an emerging issue of major importance (Section 30.3.2). Developing a better understanding of the role and temperature sensitivity of microbial systems in determining O_2 concentrations will enable a more coherent understanding of the changes and potential risks to marine ecosystems. Given the importance of microbial systems to the physical, chemical, and biological characteristics of the Ocean, it is extremely important that these systems receive greater focus, especially with regard to their response to ocean warming and acidification. This is particularly important for the DS (>1000 m), which is the most extensive habitat on the planet. In this respect, increasing our understanding of DS habitats and how they may be changing under the influence of climate change and ocean acidification is of great importance. Linkages between changes occurring in the surface layers and those associated with the DS are particularly important in light of our need to understand how rapidly changes are occurring and what the implications are for the metabolic activity and O_2 content of DS habitats.

30.7.3.4. Ocean Acidification

The rapid and largely unprecedented changes to ocean acidification represent an emerging issue given the central importance of pH and the concentration of ions such as carbonate in the biology of marine organisms (Box CC-OA). Despite the relatively short history of research on this issue, there are already a large number of laboratory and field studies that demonstrate a large range of effects across organisms, processes, and ecosystems. Key gaps (Gattuso et al., 2011) remain in our understanding of how ocean acidification will interact with other changes in the Ocean, and whether or not biological responses to ocean acidification are necessarily linear. The vulnerability of fishery species (e.g., molluscs) to ocean acidification represents an emerging issue, with a need for research to understand and develop strategies for fishery and aquaculture industries to minimize the impacts. Understanding of how carbonate structures such as coral reefs and *Halimeda* beds will respond to a rapidly acidifying ocean represents a key gap and research need, especially in understanding the rate at which consolidated carbonate structures and related habitats are likely to erode and dissolve. Interactions between ocean acidification, upwelling, and decreasing O_2 represent additional areas of concern and research. There is also a need to improve our understanding of the socioeconomic ramifications of ocean acidification (Turley and Boot, 2011; Hilmi et al., 2013).

30.7.3.5. Net Primary Productivity

Oceanic phytoplankton are responsible for approximately 50% of global net primary productivity. However, our understanding of how oceanic primary production is likely to change in a warmer and more acidified ocean is uncertain (Boxes CC-PP, CC-UP). Changes in net primary productivity will resonate through food webs and ultimately affect fisheries production. Given the central role that primary producers and their associated ecological processes play in ocean ecosystem functioning, the understanding of how net primary productivity is likely to vary at global and regional levels is improved (Sections 30.5.2, 30.5.5). At the same time, understanding how plankton communities will vary spatially and temporarily will be important in any attempt to understand how fish populations will fare in a warmer and more acidified ocean. The research challenge is to determine when and where net primary production is expected to change, coupled with research on adaptation strategies for coping with the changes to the global distribution of seafood procurement, management, and food security.

30.7.3.6. Movement of Marine Organisms and Ecosystems

Marine organisms are moving generally toward higher latitudes or deeper waters consistent with the expectation of a warming ocean. Our current understanding of which organisms and ecosystems are moving, ramifications for reorganization of ecosystems and communities, and the implications for nations is uncertain at best. Given the implications for fisheries, invasive species, and the spread of disease, it is imperative that our understanding of the movement of ecosystems is improved. Documentation of species' responses and a deeper understanding of the processes that lead to persistent range shifts, and a focus on the ecosystem, social, and economic implications of range shifts is an important research need.

30.7.3.7. Understanding Cumulative and Synergistic Impacts

Understanding cumulative and synergistic impacts is poorly developed for ocean systems. Much of our understanding has been built on experimental approaches that are focused on single stressors that respond gradually without interaction or impacts that accumulate over time (Table 30-3). Multifactorial experiments exploring the impact of combined variables (e.g., elevated temperature and acidification at the same time) will enable more realistic projections of the future to be established. Equally, developing a better understanding of how biological and ecological responses change in relation to key environmental variables should also be a goal of future research. In this regard, assumptions that responses are likely to be gradual and linear over time ultimately have little basis, yet are widespread within the scientific literature.

30.7.3.8. Reorganization of Ecosystems and Food Webs

The pervasive influence of ocean warming and acidification on the distribution, abundance, and function of organisms and processes has and will continue to drive the reorganization of ecosystems and food webs (*virtually certain*; Hoegh-Guldberg and Bruno, 2010; Poloczanska et al., 2013; Box CC-MB). One of the inevitable outcomes of differing tolerances and responses to climate change and ocean acidification is the development of novel assemblages of organisms in the near future. Such communities are likely to have no past or contemporary counterparts, and will consequently require new strategies for managing coastal areas and fisheries. Changes to a wide array of factors related or not related to climate change have the potential to drive extremely complex changes in community structure and, consequently, food web dynamics. Developing a greater capability for detecting and understanding these changes will be critical for future management of ocean and coastal resources.

30.7.3.9. Socio-ecological Resilience

Many communities depend on marine ecosystems for food and income yet our understanding of the consequences of environmental degradation is poor. For example, although there is *high confidence* that coral reefs will continue to deteriorate at current rates of climate change and ocean acidification (Gardner et al., 2003; Bruno and Selig, 2007; De'ath et al., 2012), there is relatively poor understanding of the implications for the hundreds of millions of people who depend on these important coastal ecosystems for food and livelihoods. Improving our understanding of how to reinforce socio-ecological resilience in communities affected by the deterioration of key coastal and oceanic ecosystems is central to developing effective adaptation responses to these growing challenges (Section 30.6, Tables 30-3, 30-4).

References

Adams, C.M., E. Hernandez, and J.C. Cato, 2004: The economic significance of the Gulf of Mexico related to population, income, employment, minerals, fisheries and shipping. *Ocean & Coastal Management*, **47**(**11-12**), 565-580.

Adjeroud, M., F. Michonneau, P. Edmunds, Y. Chancerelle, T. de Loma, L. Penin, L. Thibaut, J. Vidal-Dupiol, B. Salvat, and R. Galzin, 2009: Recurrent disturbances, recovery trajectories, and resilience of coral assemblages on a South Central Pacific reef. *Coral Reefs*, **28**(**3**), 775-780.

Al-Rashidi, T.B., H.I. El-Gamily, C.L. Amos, and K.A. Rakha, 2009: Sea surface temperature trends in Kuwait Bay, Arabian Gulf. *Natural Hazards*, **50**(**1**), 73-82.

Albright, R. and C. Langdon, 2011: Ocean acidification impacts multiple early life history processes of the Caribbean coral *Porites astreoides*. *Global Change Biology*, **17**(**7**), 2478-2487.

Albright, R., B. Mason, M. Miller, and C. Langdon, 2010: Ocean acidification compromises recruitment success of the threatened Caribbean coral *Acropora palmata*. *Proceedings of the National Academy of Sciences of the United States of America*, **107**(**47**), 20400-20404.

Aleksandrov, S.V., N.N. Zhigalova, and A.S. Zezera, 2009: Long-term dynamics of zooplankton in the southeastern Baltic Sea. *Russian Journal of Marine Biology*, **35**(**4**), 296-304.

Alheit, J., 2009: Consequences of regime shifts for marine food webs. *International Journal of Earth Sciences*, **98**(**2**), 261-268.

Alheit, J. and A. Bakun, 2010: Population synchronies within and between ocean basins: apparent teleconnections and implications as to physical–biological linkage mechanisms. *Journal of Marine Systems*, **79**(**3-4**), 267-285.

Allen, R. and A. Bergin, 2009: Ocean acidification: an emerging Australian environmental security challenge. *Australian Journal of Maritime and Ocean Affairs*, **1**(**2**), 49-56.

Allison, E.H., A.L. Perry, M.C. Badjeck, W.N. Adger, K. Brown, D. Conway, A.S. Halls, G.M. Pilling, J.D. Reynolds, and N.L. Andrew, 2009: Vulnerability of national economies to the impacts of climate change on fisheries. *Fish and Fisheries*, **10**(**2**), 173-196.

Alonso-Pérez, S., E. Cuevas, and X. Querol, 2011: Objective identification of synoptic meteorological patterns favouring African dust intrusions into the marine boundary layer of the subtropical Eastern North Atlantic Region. *Meteorology and Atmospheric Physics*, **113**(**3-4**), 109-124.

Amelung, B., S. Nicholls, and D. Viner, 2007: Implications of global climate change for tourism flows and seasonality. *Journal of Travel Research*, **45**(**3**), 285-296.

Andersson, A.J. and D. Gledhill, 2013: Ocean acidification and coral reefs: effects on breakdown, dissolution, and net ecosystem calcification. *Annual Review of Marine Science*, **5**, 321-348.

Andrews, O.D., N.L. Bindoff, P.R. Halloran, T. Ilyina, and C. Le Quéré, 2013: Detecting an external influence on recent changes in oceanic oxygen using an optimal fingerprinting method. *Biogeosciences*, **10**(**3**), 1799-1813.

Antonov, J.I., D. Seidov, T.P. Boyer, R.A. Locarnini, A.V. Mishonov, H.E. Garcia, O.K. Baranova, M.M. Zweng, and D.R. Johnson, 2010: World Ocean Atlas 2009, Volume 2: Salinity. In: *NOAA Atlas NESDIS 69* [Levitus, S. (ed.)]. U.S. Government Printing Office, Washington, DC, USA, 184 pp.

Archer, D., B. Buffett, and V. Brovkin, 2009: Ocean methane hydrates as a slow tipping point in the global carbon cycle. *Proceedings of the National Academy of Sciences of the United States of America*, **106**(**49**), 20596-20601.

Arístegui, J., E.D. Barton, X.A. Álvarez-Salgado, A.M.P. Santos, F.G. Figueiras, S. Kifani, S. Hernández-León, E. Mason, E. Machú, and H. Demarcq, 2009: Sub-regional ecosystem variability in the Canary Current upwelling. *Progress in Oceanography*, **83**(**1-4**), 33-48.

Arrigo, K.R., G. van Dijken, and S. Pabi, 2008: Impact of a shrinking Arctic ice cover on marine primary production. *Geophysical Research Letters*, **35**(**19**), L19603, doi:10.1029/2008GL035028.

Århun, M., T. Eldevik, L.H. Smedsrud, Ø. Skagseth, and R.B. Ingvaldsen, 2012: Quantifying the influence of Atlantic heat on Barents Sea ice variability and retreat. *Journal of Climate*, **25**(**13**), 4736-4743.

Ashok, K., S.K. Behera, S.A. Rao, H.Y. Weng, and T. Yamagata, 2007: El Niño Modoki and its possible teleconnection. *Journal of Geophysical Research: Oceans*, **112**(**C11**), C11007, doi:10.1029/2006JC003798.

Astthorsson, O.S., H. Valdimarsson, A. Gudmundsdottir, and G.J. Óskarsson, 2012: Climate-related variations in the occurrence and distribution of mackerel (*Scomber scombrus*) in Icelandic waters. *International Council for the Exploration of the Sea (ICES) Journal of Marine Science*, **69**(**7**), 1289-1297.

Ateweberhan, M. and T.R. McClanahan, 2010: Relationship between historical sea-surface temperature variability and climate change-induced coral mortality in the western Indian Ocean. *Marine Pollution Bulletin*, **60**(**7**), 964-970.

Ateweberhan, M., T.R. McClanahan, N.A.J. Graham, and C.R.C. Sheppard, 2011: Episodic heterogeneous decline and recovery of coral cover in the Indian Ocean. *Coral Reefs*, **30**(**3**), 739-752.

Auad, G., D. Roemmich, and J. Gilson, 2011: The California Current System in relation to the Northeast Pacific Ocean circulation. *Progress in Oceanography*, **91**, 576-592.

Ayón, P., S. Purca, and R. Guevara-Carrasco, 2004: Zooplankton volume trends off Peru between 1964 and 2001. *International Council for the Exploration of the Sea (ICES) Journal of Marine Science*, **61**(**4**), 478-484.

Baker, A., P.W. Glynn, and B. Riegl, 2008: Climate change and coral reef bleaching: an ecological assessment of long-term impacts, recovery trends and future outlook. *Estuarine Coastal and Shelf Science*, **80**(**4**), 435-471.

Baker-Austin, C., J.A. Trinanes, N.G.H. Taylor, R. Hartnell, A. Siitonen, and J. Martinez-Urtaza, 2012: Emerging *Vibrio* risk at high latitudes in response to ocean warming. *Nature Climate Change*, **3**(**1**), 73-77.

Bakun, A., 1990: Global climate change and intensification of coastal ocean upwelling. *Science*, **247**(**4939**), 198-201.

Bakun, A., D.B. Field, A. Redondo-Rodriguez, and S.J. Weeks, 2010: Greenhouse gas, upwelling-favorable winds, and the future of coastal ocean upwelling ecosystems. *Global Change Biology*, **16**(**4**), 1213-1228.

Banks, S.A.M.C., S.D. Ling, C.R. Johnson, M.P. Piggott, J.E. Williamson, and L.B. Beheregaray, 2010: Genetic structure of a recent climate change driven range extension. *Molecular Ecology*, **19**(**10**), 2011-2024.

Bañón, R.D., 2009: Variacións na diversidade e abundancia ictiolóxica mariña en Galicia por efectos do cambio climático. In: *Evidencias e Impacto do Cambio Climático en Galicia.* Consellería de Medio Ambiente e Desenvolvemento Sostible, Xunta de Galicia, Santiago de Compostela, Spain, pp. 355-371 (in Spanish).

Barber, R.T., 1988: Ocean basin ecosystems. In: *Concepts of Ecosystem Ecology* [Pomeroy, L.R. and J.J. Alberts (eds.)]. Springer-Verlag, New York, NY, USA, pp. 171-193.

30

Barber, R.T., J.W. Murray, and J.J. McCarthy, 1994: Biogeochemical interactions in the equatorial Pacific. *AMBIO: A Journal of the Human Environment*, **23**(**1**), 62-66.

Barlow, J., M. Kahru, and B. Mitchell, 2008: Cetacean biomass, prey consumption, and primary production requirements in the California Current ecosystem. *Marine Ecology Progress Series*, **371**, 285-295.

Barton, A., B. Hales, G.G. Waldbusser, C. Langdon, and R.A. Feely, 2012: The Pacific oyster, *Crassostrea gigas*, shows negative correlation to naturally elevated carbon dioxide levels: implications for near-term ocean acidification effects. *Limnology and Oceanography*, **57**(**3**), 698-710.

Barton, E.D., D.B. Field, and C. Roy, 2013: Canary Current upwelling: more or less? *Progress in Oceanography*, **116**, 167-178.

Batten, S.D. and A.W. Walne, 2011: Variability in northwards extension of warm water copepods in the NE Pacific. *Journal of Plankton Research*, **33**(**11**), 1643-1653.

Bauman, A.G., J.A. Burt, D.A. Feary, E. Marquis, and P. Usseglio, 2010: Tropical harmful algal blooms: an emerging threat to coral reef communities? *Marine Pollution Bulletin*, **60**(**11**), 2117-2122.

Beare, D.J., F. Burns, A. Greig, E.G. Jones, K. Peach, M. Kienzle, E. McKenzie, and D.G. Reid, 2004: Long-term increases in prevalence of North Sea fishes having southern biogeographic affinities. *Marine Ecology Progress Series*, **284**, 269-278.

Beare, D., F. Burns, E. Jones, K. Peach, and D. Reid, 2005: Red mullet migration into the northern North Sea during late winter. *Journal of Sea Research*, **53**(**3**), 205-212.

Beaudoin, Y. and L. Pendleton (eds.), 2012: *Why Value the Oceans?* Discussion paper prepared by the United Nations Environment Programme (UNEP) / Global Resource Information Database (GRID)-Arendal and Duke University's Nicholas Institute for Environmental Policy Solutions in collaboration with UNEP's The Economics of Ecosystems and Biodiversity (TEEB) Office and the UNEP Regional Seas Program, UNEP-TEEB, Geneva, Switzerland, 33 pp.

Beaugrand, G., 2004: The North Sea regime shift: evidence, causes, mechanisms and consequences. *Progress in Oceanography*, **60**(**2**), 245-262.

Beaugrand, G., 2009: Decadal changes in climate and ecosystems in the North Atlantic Ocean and adjacent seas. *Deep-Sea Research Part II: Topical Studies in Oceanography*, **56**(**8-10**), 656-673.

Beaugrand, G. and R.R. Kirby, 2010: Spatial changes in the sensitivity of Atlantic cod to climate-driven effects in the plankton. *Climate Research*, **41**(**1**), 15-19.

Beaugrand, G. and P.C. Reid, 2003: Long-term changes in phytoplankton, zooplankton and salmon related to climate. *Global Change Biology*, **9**(**6**), 801-817.

Beaugrand, G., P.C. Reid, F. Ibanez, J.A. Lindley, and M. Edwards, 2002: Reorganization of North Atlantic marine copepod biodiversity and climate. *Science*, **296**(**5573**), 1692-1694.

Beaugrand, G., K.M. Brander, J.A. Lindley, S. Souissi, and P.C. Reid, 2003: Plankton effect on cod recruitment in the North Sea. *Nature*, **426**(**6967**), 661-664.

Beaugrand, G., M. Edwards, and L. Legendre, 2010: Marine biodiversity, ecosystem functioning, and carbon cycles. *Proceedings of the National Academy of Sciences of the United States of America*, **107**(**22**), 10120-10124.

Bednaršek, N., G.A. Tarling, D.C.E. Bakker, S. Fielding, E.M. Jones, H.J. Venables, P. Ward, A. Kuzirian, B. Lézé, R.A. Feely, and E.J. Murphy, 2012: Extensive dissolution of live pteropods in the Southern Ocean. *Nature Geoscience*, **5**, 881-885.

Belkin, I.M., 2009: Rapid warming of large marine ecosystems. *Progress in Oceanography*, **81**(**1-4**), 207-213.

Bell, J.D., J.E. Johnson, and A.J. Hobday (eds.), 2011a: *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change*. Secretariat of the Pacific Community, Noumea, New Caledonia, 925 pp.

Bell, J.D., C. Reid, M.J. Batty, E.H. Allison, P. Lehodey, L. Rodwell, T.D. Pickering, R. Gillett, J.E. Johnson, A.J. Hobday, and A. Demmke, 2011b: Implications of climate change for contributions by fisheries and aquaculture to Pacific Island economies and communities. In: *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change* [Bell J.D., J.E. Johnson, and A.J. Hobday (eds.)]. Secretariat of the Pacific Community, Noumea, New Caledonia. pp. 733-802.

Bell, J.D., A. Ganachaud, P.C. Gehrke, S.P. Griffiths, A.J. Hobday, O. Hoegh-Guldberg, J.E. Johnson, R. Le Borgne, P. Lehodey, J.M. Lough, R.J. Matear, T.D. Pickering, M.S. Pratchett, A. Sen Gupta, I. Senina, and M. Waycott, 2013a: Mixed responses of tropical Pacific fisheries and aquaculture to climate change. *Nature Climate Change*, **3**, 591-599.

Bell, J.D., C. Reid, M.J. Batty, P. Lehodey, L. Rodwell, A.J. Hobday, J.E. Johnson, and A. Demmke, 2013b: Effects of climate change on oceanic fisheries in the tropical Pacific: implications for economic development and food security. *Climatic Change*, **119(1)**, 199-212.

Ben Rais Lasram, F. and D. Mouillot, 2008: Increasing southern invasion enhances congruence between endemic and exotic Mediterranean fish fauna. *Biological Invasions*, **11**(**3**), 697-711.

Bensoussan, N., J.C. Romano, J.G. Harmelin, and J. Garrabou, 2010: High resolution characterization of northwest Mediterranean coastal waters thermal regimes: to better understand responses of benthic communities to climate change. *Estuarine Coastal and Shelf Science*, **87**(**3**), 431-441.

Berke, S.K., A.R. Mahon, F.P. Lima, K.M. Halanych, D.S. Wethey, and S.A. Woodin, 2010: Range shifts and species diversity in marine ecosystem engineers: patterns and predictions for European sedimentary habitats. *Global Ecology and Biogeography*, **19**(**2**), 223-232.

Berumen, M.L. and M.S. Pratchett, 2006: Recovery without resilience: persistent disturbance and long-term shifts in the structure of fish and coral communities at Tiahura Reef, Moorea. *Coral Reefs*, **25**(**4**), 647-653.

Bethoux, J., B. Gentili, J. Raunet, and D. Tailliez, 1990: Warming trend in the western Mediterranean deep water. *Nature*, **347(6294)**, 660-662.

Beukema, J.J., R. Dekker, and J.M. Jansen, 2009: Some like it cold: populations of the tellinid bivalve *Macoma balthica* (L.) suffer in various ways from a warming climate. *Marine Ecology Progress Series*, **384**, 135-145.

Bi, H.S., W.T. Peterson, and P.T. Strub, 2011: Transport and coastal zooplankton communities in the northern California Current system. *Geophysical Research Letters*, **38(12)**, L12607, doi:10.1029/2011GL047927.

Bianchi, C.N., 2007: Biodiversity issues for the forthcoming tropical Mediterranean Sea. *Hydrobiologia*, **580(1)**, 7-21.

Blanchard, J.L., S. Jennings, R. Holmes, J. Harle, G. Merino, J.I. Allen, J. Holt, N.K. Dulvy, and M. Barange, 2012: Potential consequences of climate change for primary production and fish production in large marine ecosystems. *Philosophical Transactions of the Royal Society B*, **367**(**1605**), 2979-2989.

Block, B.A., I.D. Jonsen, S.J. Jorgensen, A.J. Winship, S.A. Shaffer, S.J. Bograd, E.I. Hazen, D.G. Foley, G.A. Breed, A.-L. Harrison, J.E. Ganong, A. Swithenbank, M. Castleton, H. Dewar, B.R. Mate, G.L. Shillinger, K.M. Schaefer, S.R. Benson, M.J. Weise, R.W. Henry, and D.P. Costa, 2011: Tracking apex marine predator movements in a dynamic ocean. *Nature*, **475(7354)**, 86-90.

Bode, A., R. Anadón, X.A.G. Morán, E. Nogueira, E. Teira, and M. Varela, 2011: Decadal variability in chlorophyll and primary production off NW Spain. *Climate Research*, **48**(**2**), 293-305.

Bograd, S.J., C.G. Castro, E. Di Lorenzo, D.M. Palacios, H. Bailey, W. Gilly, and F.P. Chavez, 2008: Oxygen declines and the shoaling of the hypoxic boundary in the California Current. *Geophysical Research Letters*, **35**(**12**), L12607, doi:10.1029/2008GL034185.

Bonfils, C. and B.D. Santer, 2011: Investigating the possibility of a human component in various pacific decadal oscillation indices. *Climate Dynamics*, **37**(**7**), 1457-1468.

Bonnet, D., A. Richardson, R. Harris, A. Hirst, G. Beaugrand, M. Edwards, S. Ceballos, R. Diekman, A. Lopez-Urrutia, L. Valdes, F. Carlotti, J.C. Molinero, H. Weikert, W. Greve, D. Lucic, A. Albaina, N.D. Yahia, S.F. Umani, A. Miranda, A. dos Santos, K. Cook, S. Robinson, and M.L.F. de Puelles, 2005: An overview of *Calanus helgolandicus* ecology in European waters. *Progress in Oceanography*, **65**(**1**), 1-53.

Borgerson, S.G., 2008: Arctic meltdown: the economic and security implications of global warming. *Foreign Affairs*, **87**(**2**), 63-77.

Bostock, J., B. McAndrew, R. Richards, K. Jauncey, T. Telfer, K. Lorenzen, D. Little, L. Ross, N. Handisyde, I. Gatward, and R. Corner, 2010: Aquaculture: global status and trends. *Philosophical Transactions of the Royal Society B*, **365**, 2897-2912.

Boyer, T.P., 2005: Linear trends in salinity for the World Ocean, 1955-1998. *Geophysical Research Letters*, **32**(**1**), L01604, doi:10.1029/2004GL021791.

Boyle, A., 2012: Law of the Sea perspectives on climate change. *The International Journal of Marine and Coastal Law*, **27**(**4**), 831-838.

Bozkurt, D. and O.L. Sen, 2011: Precipitation in the Anatolian Peninsula: sensitivity to increased SSTs in the surrounding seas. *Climate Dynamics*, **36**(**3-4**), 711-726.

Brevik, E.C., and J.A. Homburg, 2004: A 5000 year record of carbon sequestration from a coastal lagoon and wetland complex, Southern California, USA. *Catena*, **57**(**3**), 221-232.

Brown, B.E., R.P. Dunne, N. Phongsuwan, and P.J. Somerfield, 2011: Increased sea level promotes coral cover on shallow reef flats in the Andaman Sea, eastern Indian Ocean. *Coral Reefs*, **30**(**4**), 867-878.

Brown, C.W. and J.A. Yoder, 1994: Coccolithophorid blooms in the global ocean. *Journal of Geophysical Research: Oceans*, **99**(**C4**), 7467-7482.

Brown, J.H., J.F. Gillooly, A.P. Allen, V.M. Savage, and G.B. West, 2004: Toward a metabolic theory of ecology. *Ecology*, **85**(**7**), 1771-1789.

Brundrit, G.B., 1995: Trends in southern African sea level: statistical analysis and interpretation. *South African Journal of Marine Science*, **16(1)**, 9-17.

Bruno, J.F. and E.R. Selig, 2007: Regional decline of coral cover in the Indo-Pacific: timing, extent, and subregional comparisons. *PLoS ONE*, **2**(**8**), e711, doi:10.1371/journal.pone.0000711.

Buesseler, K.O., C.H. Lamborg, P.W. Boyd, P.J. Lam, T.W. Trull, R.R. Bidigare, J.K.B. Bishop, K.L. Casciotti, F. Dehairs, M. Elskens, M. Honda, D.M. Karl, D.A. Siegel, M.W. Silver, D.K. Steinberg, J. Valdes, B. Van Mooy, and S. Wilson, 2007: Revisiting carbon flux through the ocean's twilight zone. *Science*, **316**(**5824**), 567-570.

Buongiorno Nardelli, B., S. Colella, R. Santoleri, M. Guarracino, and A. Kholod, 2010: A re-analysis of Black Sea surface temperature. *Journal of Marine Systems*, **79**(**1-2**), 50-64.

Burke, L.M. and J. Maidens, 2004: *Reefs at Risk in the Caribbean*. World Resources Institute (WRI), Washington, DC, USA, 80 pp.

Burke, L.M., L. Selig, and M. Spalding, 2002: *Reefs at Risk in Southeast Asia*. World Resources Institute (WRI), Washington, DC, USA, 76 pp.

Burke, L.M., K. Reytar, M. Spalding, and A. Perry, 2011: *Reefs at Risk Revisited*. World Resources Institute (WRI), Washington, DC, USA, 130 pp.

Burrows, M.T., D.S. Schoeman, L.B. Buckley, P. Moore, E.S. Poloczanska, K.M. Brander, C. Brown, J.F. Bruno, C.M. Duarte, B.S. Halpern, J. Holding, C.V. Kappel, W. Kiessling, M.I. O'Connor, J.M. Pandolfi, C. Parmesan, F.B. Schwing, W.J. Sydeman, and A.J. Richardson, 2011: The pace of shifting climate in marine and terrestrial ecosystems. *Science*, **334**(**6056**), 652-655.

Busby, J.W., 2009: The climate-security connection: what it means for the poor. In: *Climate Change and Global Poverty: A Billion Lives in the Balance* [Brainard, L., A. Jones, and N. Purvis (eds.)]. Brookings Institute Press, Washington, DC, USA, pp. 155-180.

Byrne, R.H., S. Mecking, R.A. Feely, and X. Liu, 2010: Direct observations of basin-wide acidification of the North Pacific Ocean. *Geophysical Research Letters*, **37**(**2**), L02601, doi:10.1029/2009GL040999.

Cai, R. and H. Tan, 2010: Influence of interdecadal climate variation over East Asia on offshore ecological system of China. *Journal of Oceanography in Taiwan Strait*, **29**(**2**), 173-183 (in Chinese).

Cai, R., J. Chen, and R. Huang, 2006: The response of marine environment in the offshore area of China and its adjacent ocean to recent global climate change. *Chinese Journal of Atmospheric Sciences*, **30**(**5**), 1019-1033 (in Chinese).

Cai, R., Q. Zhang, and Q. Qi, 2009: Spatial and temporal oscillation and long-term variation in sea surface temperature field of the South China Sea. *Journal of Oceanography in Taiwan Strait*, **29**(**2**), 173-183 (in Chinese).

Cai, R., J. Chen, and H. Tan, 2011: Variations of the sea surface temperature in the offshore area of China and their relationship with the East Asian monsoon under the global warming. *Climatic and Environmental Research*, **16**(**1**), 94-104 (in Chinese).

Cai, W., 2006: Antarctic ozone depletion causes an intensification of the Southern Ocean super-gyre circulation. *Geophysical Research Letters*, **33**(**3**), L03712, doi:10.1029/2005GL024911.

Cai, W. and T. Cowan, 2007: Trends in Southern Hemisphere circulation in IPCC AR4 models over 1950-99: ozone depletion versus greenhouse forcing. *Journal of Climate*, **20**(**4**), 681-693.

Cai, W., M. Lengaigne, S. Borlace, M. Collins, T. Cowan, M.J. McPhaden, A. Timmermann, S. Power, J. Brown, C. Menkes, A. Ngari, E.M. Vincent, and M.J. Widlansky, 2012: More extreme swings of the South Pacific convergence zone due to greenhouse warming. *Nature*, **488(7411)**, 365-369.

Caldeira, K. and M.E. Wickett, 2003: Oceanography: anthropogenic carbon and ocean pH. *Nature*, **425**(**6956**), 365, doi:10.1038/425365a .

Callaghan, J. and S.B. Power, 2011: Variability and decline in the number of severe tropical cyclones making land-fall over eastern Australia since the late nineteenth century. *Climate Dynamics*, **37**(**3**), 647-662.

Calvo, E., R. Simó, R. Coma, M. Ribes, J. Pascual, A. Sabatés, J.M. Gili, and C. Pelejero, 2011: Effects of climate change on Mediterranean marine ecosystems: the case of the Catalan Sea. *Climate Research*, **50**(**1**), 1-29.

Cantin, N.E., A.L. Cohen, K.B. Karnauskas, A.M. Tarrant, and D.C. McCorkle, 2010: Ocean warming slows coral growth in the central Red Sea. *Science*, **329**(**5989**), 322-325.

Carrigan, A.D. and M.L. Puotinen, 2011: Assessing the potential for tropical cyclone induced sea surface cooling to reduce thermal stress on the world's coral reefs. *Geophysical Research Letters*, **38**(**23**), L23604, doi:10.1029/2011GL049722.

Casini, M., G. Kornilovs, M. Cardinale, C. Möllmann, W. Grygiel, P. Jonsson, T. Raid, J. Flinkman, and V. Feldman, 2011: Spatial and temporal density dependence regulates the condition of the central Baltic Sea clupeids: compelling evidence using an extensive international acoustic survey. *Population Ecology*, **53**(**4**), 511-523.

Cerrano, C., G. Bavestrello, C. Bianchi, R. Cattaneo-Vietti, S. Bava, C. Morganti, C. Morri, P. Picco, G. Sara, and S. Schiaparelli, 2000: A catastrophic mass-mortality episode of gorgonians and other organisms in the Ligurian Sea (North-western Mediterranean), summer 1999. *Ecology Letters*, **3**(**4**), 284-293.

Chan, F., J.A. Barth, J. Lubchenco, A. Kirincich, H. Weeks, W.T. Peterson, and B.A. Menge, 2008: Emergence of anoxia in the California Current large marine ecosystem. *Science*, **319**(**5865**), 920, doi:10.1126/science.1149016.

Chan, W.H., Y.L. Mak, J.J. Wu, L. Jin, W.H. Sit, J.C. Lam, Y. Sadovy de Mitcheson, L.L. Chan, P.K. Lam, and M.B. Murphy, 2011: Spatial distribution of ciguateric fish in the Republic of Kiribati. *Chemosphere*, **84**(**1**), 117-123.

Chang, Y., M.-A. Lee, K.-T. Lee, and K.-T. Shao, 2013: Adaptation of fisheries and ariculture management to extreme oceanic environmental changes and climate variability in Taiwan. *Marine Policy*, **38**, 476-482.

Chassot, E., F. Mélin, O. Le Pape, and D. Gascuel, 2007: Bottom-up control regulates fisheries production at the scale of eco-regions in European seas. *Marine Ecology Progress Series*, **343**, 45-55.

Chassot, E., S. Bonhommeau, N.K. Dulvy, F. Mélin, R. Watson, D. Gascuel, and O. Le Pape, 2010: Global marine primary production constrains fisheries catches. *Ecology Letters*, **13**(**4**), 495-505.

Chavez, F.P. and M. Messie, 2009: A comparison of Eastern Boundary Upwelling Ecosystems. *Progress in Oceanography*, **83**(**1-4**), 80-96.

Chavez, F.P., J. Ryan, S.E. Lluch-Cota, and C.M. Ñiquen, 2003: From anchovies to sardines and back: multidecadal change in the Pacific Ocean. *Science*, **299**(**5604**), 217-221.

Chavez, F.P., M. Messie, and J.T. Pennington, 2011: Marine primary production in relation to climate variability and change. *Annual Review of Marine Science*, **3**, 227-260.

Checkley, D.M. and J.A. Barth, 2009: Patterns and processes in the California Current System. *Progress in Oceanography*, **83**(**1-4**), 49-64.

Chelton, D.B., P.A. Bernal, and J.A. McGowan, 1982: Large-scale interannual physical and biological interaction in the California Current. *Journal of Marine Research*, **40**(**4**), 1095-1125.

Chen, T.-R., K.-F. Yu, Q. Shi, S. Li, G.J. Price, R. Wang, M.-X. Zhao, T.-G. Chen, and J.-X. Zhao, 2009: Twenty-five years of change in scleractinian coral communities of Daya Bay (northern South China Sea) and its response to the 2008 AD extreme cold climate event. *Chinese Science Bulletin*, **54**(**12**), 2107-2117.

Cheng, X. and Y. Qi, 2007: Trends of sea level variations in the South China Sea from merged altimetry data. *Global and Planetary Change*, **57**(**3-4**), 371-382.

Cheung, W.W.L., V.W.Y. Lam, J.L. Sarmiento, K. Kearney, R. Watson, D. Zeller, and D. Pauly, 2010: Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Global Change Biology*, **16**(**1**), 24-35.

Cheung, W.W.L., J. Dunne, J.L. Sarmiento, and D. Pauly, 2011: Integrating ecophysiology and plankton dynamics into projected maximum fisheries catch potential under climate change in the Northeast Atlantic. *International Council for the Exploration of the Sea (ICES) Journal of Marine Science*, **68**(**6**), 1008-1018.

Cheung, W.W.L., J.K. Pinnegar, G. Merino, M.C. Jones, and M. Barange, 2012: Review of climate change impacts on marine fisheries in the UK and Ireland. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **22**, 368-388.

Chhak, K.C., E. Di Lorenzo, N. Schneider, and P.F. Cummins, 2009: Forcing of low-frequency ocean variability in the Northeast Pacific. *Journal of Climate*, **22**(**5**), 1255-1276.

Chiba, S., K. Tadokoro, H. Sugisaki, and T. Saino, 2006: Effects of decadal climate change on zooplankton over the last 50 years in the western subarctic North Pacific. *Global Change Biology*, **12**(**5**), 907-920.

Chiba, S., M.N. Aita, K. Tadokoro, T. Saino, H. Sugisaki, and K. Nakata, 2008: From climate regime shifts to lower-trophic level phenology: synthesis of recent progress in retrospective studies of the western North Pacific. *Progress in Oceanography*, **77**(**2-3**), 112-126.

China-SNAP, 2011: *The Second National Chinese Assessment Report on Climate Change: General Abstract*. Jointly issued by the Chinese Ministry of Science and Technology, the China Meteorological Administration, and the Chinese Academy of Sciences, Science Press, Beijing, China, 44 pp.

Christian, J.R. and R. Murtugudde, 2003: Tropical Atlantic variability in a coupled physical–biogeochemical ocean model. *Deep-Sea Research Part II: Topical Studies in Oceanography*, **50**(**22-26**), 2947-2969.

Church, J.A., N.J. White, R. Coleman, K. Lambeck, and J.X. Mitrovica, 2004: Estimates of the regional distribution of sea level rise over the 1950-2000 period. *Journal of Climate*, **17**(**13**), 2609-2625.

Church, J.A., N.J. White, and J.R. Hunter, 2006: Sea-level rise at tropical Pacific and Indian Ocean islands. *Global and Planetary Change*, **53**(**3**), 155-168.

CIESM, 2008: Climate warming and related changes in Mediterranean marine biota. In: *CIESM Workshop Monographs, No. 35* [Briand, F. (ed.)]. Commission Internationale pour l'Exploration Scientifique de la Méditerranée (CIESM) [The Mediterranean Science Commission], Monaco, 152 pp.

Cinner, J.E., T.R. McClanahan, T.M. Daw, N.A. Graham, J. Maina, S.K. Wilson, and T.P. Hughes, 2009: Linking social and ecological systems to sustain coral reef fisheries. *Current Biology*, **19**(**3**), 206-212.

Clark, C.O., J.E. Cole, and P.J. Webster, 2000: Indian Ocean SST and Indian summer rainfall: predictive relationships and their decadal variability. *Journal of Climate*, **13**(**14**), 2503-2519.

Clifton, J., 2009: Science, funding and participation: key issues for marine protected area networks and the Coral Triangle Initiative. *Environmental Conservation*, **36**(**2**), 91-96.

Cocco, V., F. Joos, M. Steinacher, T.L. Frölicher, L. Bopp, J. Dunne, M. Gehlen, C. Heinze, J. Orr, and A. Oschlies, 2013: Oxygen and indicators of stress for marine life in multi-model global warming projections. *Biogeosciences*, **10**(**3**), 1849-1868.

Cochrane, K.L., N.L. Andrew, and A.M. Parma, 2011: Primary fisheries management: a minimum requirement for provision of sustainable human benefits in small-scale fisheries. *Fish and Fisheries*, **12**(**3**), 275-288.

Cockcroft, A.C., D. van Zyl, and L. Hutchings, 2008: Large-scale changes in the spatial distribution of South African West Coast rock lobsters: an overview. *African Journal of Marine Science*, **30**(**1**), 149-159.

Collie, J.S., A.D. Wood, and H.P. Jeffries, 2008: Long-term shifts in the species composition of a coastal fish community. *Canadian Journal of Fisheries and Aquatic Sciences*, **65**(**7**), 1352-1365.

Collins, M., S.-I. An, W. Cai, A. Ganachaud, E. Guilyardi, F.-F. Jin, M. Jochum, M. Lengaigne, S. Power, and A. Timmermann, 2010: The impact of global warming on the tropical Pacific Ocean and El Niño. *Nature Geoscience*, **3**(**6**), 391-397.

Colwell, R.R., 1996: Global climate and infectious disease: the cholera paradigm. *Science*, **274**(**5295**), 2025-2031.

Coma, R., M. Ribes, E. Serrano, E. Jiménez, J. Salat, and J. Pascual, 2009: Global warming-enhanced stratification and mass mortality events in the Mediterranean. *Proceedings of the National Academy of Sciences of the United States of America*, **106**(**15**), 6176-6181.

Conley, D.J., S. Bjorck, E. Bonsdorff, J. Carstensen, G. Destouni, B.G. Gustafsson, S. Hietanen, M. Kortekaas, H. Kuosa, H.E. Meier, B. Muller-Karulis, K. Nordberg, A. Norkko, G. Nurnberg, H. Pitkanen, N.N. Rabalais, R. Rosenberg, O.P. Savchuk, C.P. Slomp, M. Voss, F. Wulff, and L. Zillen, 2009: Hypoxia-related processes in the Baltic Sea. *Environmental Science & Technology*, **43**(**10**), 3412-3420.

Conversi, A., S. Fonda Umani, T. Peluso, J.C. Molinero, A. Santojanni, and M. Edwards, 2010: The Mediterranean Sea regime shift at the end of the 1980s, and intriguing parallelisms with other European basins. *PLoS ONE*, **5**(**5**), e10633, doi:10.1371/journal.pone.0010633.

Cooley, S.R. and S.C. Doney, 2009: Anticipating ocean acidification's economic consequences for commercial fisheries. *Environmental Research Letters*, **4**(**2**), 024007, doi:10.1088/1748-9326/4/2/024007.

Costello, A., M. Abbas, A. Allen, S. Ball, S. Bell, R. Bellamy, S. Friel, N. Groce, A. Johnson, M. Kett, M. Lee, C. Levy, M. Maslin, D. McCoy, B. McGuire, H. Montgomery, D. Napier, C. Pagel, J. Patel, J.A. de Oliveira, N. Redclift, H. Rees, D. Rogger, J. Scott, J. Stephenson, J. Twigg, J. Wolff, and C. Patterson, 2009: Managing the health effects of climate change. *Lancet*, **373**(**9676**), 1693-1733.

Crain, C.M., K. Kroeker, and B.S. Halpern, 2008: Interactive and cumulative effects of multiple human stressors in marine systems. *Ecology Letters*, **11**(**12**), 1304-1315.

Crawford, R.J.M., A.J. Tree, P.A. Whittington, J. Visagie, L. Upfold, K.J. Roxburg, A.P. Martin, and B.M. Dyer, 2008: Recent distributional changes of seabirds in South Africa: is climate having an impact? *African Journal of Marine Science*, **30**(**1**), 189-193.

Crisci, C., N. Bensoussan, J.C. Romano, and J. Garrabou, 2011: Temperature anomalies and mortality events in marine communities: insights on factors behind differential mortality impacts in the NW Mediterranean. *PLoS ONE*, **6**(**9**), e23814, doi:10.1371/journal.pone.0023814.

Cruz, A.M. and E. Krausmann, 2008: Damage to offshore oil and gas facilities following hurricanes Katrina and Rita: an overview. *Journal of Loss Prevention in the Process Industries*, **21**(**6**), 620-626.

Cubillos, J.C., S.W. Wright, G. Nash, M.F. de Salas, B. Griffiths, B. Tilbrook, A. Poisson, and G.M. Hallegraeff, 2007: Calcification morphotypes of the coccolithophorid *Emiliania huxleyi* in the Southern Ocean: changes in 2001 to 2006 compared to historical data. *Marine Ecology Progress Series*, **348**, 47-54.

Cury, P. and L. Shannon, 2004: Regime shifts in upwelling ecosystems: observed changes and possible mechanisms in the northern and southern Benguela. *Progress in Oceanography*, **60**(**2-4**), 223-243.

Cushing, D.H., 1990: Plankton production and year-class strength in fish populations – an update of the match/mismatch hypothesis. In: *Advances in Marine Biology*, *Vol. 26* [Blaxter, J.H.S. and A.J. Southward (eds.)]. Academic Press, San Diego, CA, USA and London, UK, pp. 249-293.

Dalpadado, P., R.B. Ingvaldsen, L.C. Stige, B. Bogstad, T. Knutsen, G. Ottersen, and B. Ellertsen, 2012: Climate effects on Barents Sea ecosystem dynamics. *International Council for the Exploration of the Sea (ICES) Journal of Marine Science*, **69**(**7**), 1303-1316.

Danovaro, R., S. Fonda Umani, and A. Pusceddu, 2009: Climate change and the potential spreading of marine mucilage and microbial pathogens in the Mediterranean Sea. *PLoS ONE*, **4**(**9**), e7006, doi:10.1371/journal.pone.0007006.

Danovaro, R., C. Corinaldesi, G. D'Onghia, B. Galil, C. Gambi, A.J. Gooday, N. Lampadariou, G.M. Luna, C. Morigi, K. Olu, P. Polymenakou, E. Ramirez-Llodra, A. Sabbatini, F. Sardà, M. Sibuet, and A. Tselepides, 2010: Deep-sea biodiversity in the Mediterranean Sea: the known, the unknown, and the unknowable. *PLoS ONE*, **5**(**8**), e11832, doi:10.1371/journal.pone.0011832.

De'ath, G., K.E. Fabricius, H. Sweatman, and M. Puotinen, 2012: The 27-year decline of coral cover on the Great Barrier Reef and its causes. *Proceedings of the National Academy of Sciences of the United States of America*, **109**(**44**), 17995-17999.

Della Patrona, L., B. Beliaeff, and T. Pickering, 2011: Mitigation of sea level rise effects by addition of sediment to shrimp ponds. *Aquaculture Environment Interactions*, **2**, 27-38.

Demarcq, H., 2009: Trends in primary production, sea surface temperature and wind in upwelling systems (1998-2007). *Progress in Oceanography*, **83**(**1**), 376-385.

Deser, C., A.S. Phillips, and J.W. Hurrell, 2004: Pacific interdecadal climate variability: linkages between the tropics and the North Pacific during boreal winter since 1900. *Journal of Climate*, **17**(**16**), 3109-3124.

Di Lorenzo, E., N. Schneider, K.M. Cobb, P.J.S. Franks, K. Chhak, A.J. Miller, J.C. McWilliams, S.J. Bograd, H. Arango, E. Curchitser, T.M. Powell, and P. Rivière, 2008: North Pacific Gyre Oscillation links ocean climate and ecosystem change. *Geophysical Research Letters*, **35**(**8**), L08607, doi:10.1029/2007GL032838.

Diaz-Almela, E., N. Marbà, and C.M. Duarte, 2007: Consequences of Mediterranean warming events in seagrass (*Posidonia oceanica*) flowering records. *Global Change Biology*, **13**(**1**), 224-235.

Dixson, D.L., G.P. Jones, P.L. Munday, S. Planes, M.S. Pratchett, M. Srinivasan, C. Syms, and S.R. Thorrold, 2008: Coral reef fish smell leaves to find island homes. *Proceedings of the Royal Society B*, **275**(**1653**), 2831-2839.

Dixson, D.L., P.L. Munday, and G.P. Jones, 2010: Ocean acidification disrupts the innate ability of fish to detect predator olfactory cues. *Ecology Letters*, **13**(**1**), 68-75.

Doney, S.C., V.J. Fabry, R.A. Feely, and J.A. Kleypas, 2009: Ocean acidification: the other CO_2 problem. *Annual Review of Marine Science*, **1**, 169-192.

Donner, S.D., C.J. Kucharik, and J.A. Foley, 2004: Impact of changing land use practices on nitrate export by the Mississippi River. *Global Biogeochemical Cycles*, **18**(**1**), GB1028, doi:10.1029/2003GB002093.

Donner, S.D., W.J. Skirving, C.M. Little, M. Oppenheimer, and O. Hoegh-Guldberg, 2005: Global assessment of coral bleaching and required rates of adaptation under climate change. *Global Change Biology*, **11**(**12**), 2251-2265.

Donner, S.D., T.R. Knutson, and M. Oppenheimer, 2007: Model-based assessment of the role of human-induced climate change in the 2005 Caribbean coral bleaching event. *Proceedings of the National Academy of Sciences of the United States of America*, **104**(**13**), 5483-5488.

Donner, S.D., T. Kirata, and C. Vieux, 2010: Recovery from the 2004 coral bleaching event in the Gilbert Islands, Kiribati. *Atoll Research Bulletin*, **587**, 1-27.

Dove, S., D.I. Kline, O. Pantos, F.E. Angly, G.W. Tyson, and O. Hoegh-Guldberg, 2013: Future reef decalcification under a business-as-usual CO_2 emission scenario. *Proceedings of the National Academy of Sciences of the United States of America*, **110**(**38**), 15342-15347.

Drinkwater, K.F., 2006: The regime shift of the 1920s and 1930s in the North Atlantic. *Progress in Oceanography*, **68**(**2-4**), 134-151.

Duarte, C.M., J. Middelburg, and N. Caraco, 2005: Major role of marine vegetation on the oceanic carbon cycle. *Biogeosciences*, **2**(**1**), 1-8.

Dulvy, N.K., S.I. Rogers, S. Jennings, V. Stelzenmüller, S.R. Dye, and H.R. Skjoldal, 2008: Climate change and deepening of the North Sea fish assemblage: a biotic indicator of warming seas. *Journal of Applied Ecology*, **45**(**4**), 1029-1039.

Durack, P.J. and S.E. Wijffels, 2010: Fifty-year trends in global ocean salinities and their relationship to broad-scale warming. *Journal of Climate*, **23**(**16**), 4342-4362.

Durack, P.J., S.E. Wijffels, and R.J. Matear, 2012: Ocean salinities reveal strong global water cycle intensification during 1950 to 2000. *Science*, **336**(**6080**), 455-458.

Eakin, C.M., J.A. Morgan, S.F. Heron, T.B. Smith, G. Liu, L. Alvarez-Filip, B. Baca, E. Bartels, C. Bastidas, C. Bouchon, M. Brandt, A.W. Bruckner, L. Bunkley-Williams, A. Cameron, B.D. Causey, M. Chiappone, T.R.L. Christensen, M.J.C. Crabbe, O. Day, E. de la Guardia, G. Díaz-Pulido, D. DiResta, D.L. Gil-Agudelo, D.S. Gilliam, R.N. Ginsburg, S. Gore, H.M. Guzmán, J.C. Hendee, E.A. Hernández-Delgado, E. Husain, C.F.G. Jeffrey, R.J. Jones, E. Jordán-Dahlgren, L.S. Kaufman, D.I. Kline, P.A. Kramer, J.C. Lang, D. Lirman, J. Mallela, C. Manfrino, J.-P. Maréchal, K. Marks, J. Mihaly, W.J. Miller, E.M. Mueller, E.M. Muller, C.A. Orozco Toro, H.A. Oxenford, D. Ponce-Taylor, N. Quinn, K.B. Ritchie, S. Rodríguez, A.R. Ramírez, S. Romano, J.F. Samhouri, J.A. Sánchez, G.P. Schmahl, B.V. Shank, W.J. Skirving, S.C.C. Steiner, E. Villamizar, S.M. Walsh, C. Walter, E. Weil, E.H. Williams, K.W. Roberson, and Y. Yusuf, 2010: Caribbean corals in crisis: record thermal stress, bleaching, and mortality in 2005. *PLoS ONE*, **5**(**11**), e13969, doi:10.1371/journal.pone.0013969.

Edgar, G.J., S.A. Banks, M. Brandt, R.H. Bustamante, A. Chiriboga, S.A. Earle, L.E. Garske, P.W. Glynn, J.S. Grove, S. Henderson, C.P. Hickman, K.A. Miller, F. Rivera, and G.M. Wellington, 2010: El Niño, grazers and fisheries interact to greatly elevate extinction risk for Galapagos marine species. *Global Change Biology*, **16**(**10**), 2876-2890.

Edwards, M., 2004: Continuous plankton records: Plankton Atlas of the North Atlantic Ocean 1958-1999: Preface. *Marine Ecology Progress Series*, **(Suppl. CPR Atlas)**, 1-2, www.int-res.com/journals/meps/cpr-plankton-atlas-2004/.

Edwards, M. and A.J. Richardson, 2004: Impact of climate change on marine pelagic phenology and trophic mismatch. *Nature*, **430**(**7002**), 881-884.

Edwards, M., G. Beaugrand, G.C. Hays, J.A. Koslow, and A.J. Richardson, 2010: Multi-decadal oceanic ecological datasets and their application in marine policy and management. *Trends in Ecology & Evolution*, **25**(**10**), 602-610.

Ellingsen, I.H., P. Dalpadado, D. Slagstad, and H. Loeng, 2008: Impact of climatic change on the biological production in the Barents Sea. *Climatic Change*, **87**(**1**), 155-175.

Emanuel, K., 2005: Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, **436**(**7051**), 686-688.

Eriksen, E., R. Ingvaldsen, J.E. Stiansen, and G.O. Johansen, 2012: Thermal habitat for 0-group fish in the Barents Sea; how climate variability impacts their density, length, and geographic distribution. *International Council for the Exploration of the Sea (ICES) Journal of Marine Science*, **69**(**5**), 870-879.

Fabricius, K.E., C. Langdon, S. Uthicke, C. Humphrey, S. Noonan, G. De'ath, R. Okazaki, N. Muehllehner, M.S. Glas, and J.M. Lough, 2011: Losers and winners in coral reefs acclimatized to elevated carbon dioxide concentrations. *Nature Climate Change*, **1**(**3**), 165-169.

Falkowski, P.G., T. Algeo, L. Codispoti, C. Deutsch, S. Emerson, B. Hales, R.B. Huey, W.J. Jenkins, L.R. Kump, L.A. Levin, T.W. Lyons, N.B. Nelson, O.S. Schofield, R. Summons, L.D. Talley, E. Thomas, F. Whitney, and C.B. Pilcher, 2011: Ocean deoxygenation: past, present, and future. *Eos*, **92**(**46**), 409-410.

FAO, 2012. *The State of the World Fisheries and Aquaculture 2012*. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, 209 pp.

Feely, R.A., C.L. Sabine, K. Lee, W. Berelson, J. Kleypas, V.J. Fabry, and F.J. Millero, 2004: Impact of anthropogenic CO_2 on the $CaCO_3$ system in the oceans. *Science*, **305**(**5682**), 362-366.

Feely, R.A., C.L. Sabine, J.M. Hernandez-Ayon, D. Ianson, and B. Hales, 2008: Evidence for upwelling of corrosive "acidified" water onto the continental shelf. *Science*, **320**(**5882**), 1490-1492.

Feely, R.A., S.C. Doney, and S.R. Cooley, 2009: Ocean acidification: present conditions and future changes in a high-CO_2 world. *Oceanography*, **22**(**4**), 36-47.

Feely, R.A., C.L. Sabine, R.H. Byrne, F.J. Millero, A.G. Dickson, R. Wanninkhof, A. Murata, L.A. Miller, and D. Greeley, 2012: Decadal changes in the aragonite and calcite saturation state of the Pacific Ocean. *Global Biogeochemical Cycles*, **26**(**3**), GB3001, doi:10.1029/2011GB004157.

Firth, L.B., A.M. Knights, and S.S. Bell, 2011: Air temperature and winter mortality: implications for the persistence of the invasive mussel, *Perna viridis* in the intertidal zone of the south-eastern United States. *Journal of Experimental Marine Biology and Ecology*, **400**(**1-2**), 250-256.

Fonselius, S. and J. Valderrama, 2003: One hundred years of hydrographic measurements in the Baltic Sea. *Journal of Sea Research*, **49**(**4**), 229-241.

Form, A.U. and U. Riebesell, 2012: Acclimation to ocean acidification during long-term CO_2 exposure in the cold-water coral *Lophelia pertusa*. *Global Change Biology*, **18**(**3**), 843-853.

Friedrich, T., A. Timmermann, A. Abe-Ouchi, N.R. Bates, M.O. Chikamoto, M.J. Church, J.E. Dore, D.K. Gledhill, M. Gonzalez-Davila, M. Heinemann, T. Ilyina, J.H. Jungclaus, E. McLeod, A. Mouchet, and J.M. Santana-Casiano, 2012: Detecting regional anthropogenic trends in ocean acidification against natural variability. *Nature Climate Change*, **2**(**3**), 167-171.

Frieler, K., M. Meinshausen, A. Golly, M. Mengel, K. Lebek, S.D. Donner, and O. Hoegh-Guldberg, 2012: Limiting global warming to 2°C is unlikely to save most coral reefs. *Nature Climate Change*, **3**, 165-170.

Frontier Economics, Ltd., 2013: *Economics of Climate Resilience, Natural Environment Theme: Sea Fish, CA0401.* Report prepared for the Department for Environment Food and Rural Affairs (DEFRA) and the Devolved Administrations (DAs) by Frontier Economics, Ltd. supported by Irbaris LLP and Ecofys UK, Ltd., DEFRA, London, UK, 101 pp.

Fu, B.-J., C.-H. Su, Y.-P. Wei, I.R. Willett, Y.-H. Lü, and G.-H. Liu, 2011: Double counting in ecosystem services valuation: causes and countermeasures. *Ecological Research*, **26**(**1**), 1-14.

Galil, B.S., 2008: Alien species in the Mediterranean Sea – which, when, where, why? *Hydrobiologia*, **606**(**1**), 105-116.

Galil, B.S., 2011: The alien crustaceans in the Mediterranean Sea: an historical review. In: *In the Wrong Place –Alien Marine Crustaceans: Distribution, Biology and Impacts* [Galil, B.S., P.F. Clark, and J.T. Carlton (eds.)]. Springer, Dordrecht, Netherlands, pp. 377-401.

Ganachaud, A., A. Sen Gupta, J. Orr, S. Wijffels, K. Ridgway, M. Hemer, C. Maes, C. Steinberg, A. Tribollet, B. Qiu, and K. J., 2011: Observed and expected changes to the tropical Pacific Ocean. In: *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change* [Bell, J.D., J.E. Johnson, and A.J. Hobday (eds.)]. Secretariat of the Pacific Community, Noumea, New Caledonia. pp. 101-187.

Gardner, T.A., I.M. Côté, J.A. Gill, A. Grant, and A.R. Watkinson, 2003: Long-term region-wide declines in Caribbean corals. *Science*, **301**(**5635**), 958-960.

Garrabou, J., R. Coma, N. Bensoussan, M. Bally, P. Chevaldonné, M. Cigliano, D. Diaz, J.G. Harmelin, M.C. Gambi, D.K. Kersting, J.B. Ledoux, C. Lejeusne, C. Linares, C. Marschal, T. Pérez, M. Ribes, J.C. Romano, E. Serrano, N. Teixido, O. Torrents, M. Zabala, F. Zuberer, and C. Cerrano, 2009: Mass mortality in Northwestern Mediterranean rocky benthic communities: effects of the 2003 heat wave. *Global Change Biology*, **15**(**5**), 1090-1103.

Garreaud, R.D. and M. Falvey, 2009: The coastal winds off western subtropical South America in future climate scenarios. *International Journal of Climatology*, **29**(**4**), 543-554.

Gattuso, J.-P., J. Bijma, M. Gehlen, U. Riebesell, and C. Turley, 2011: Ocean acidification: knowns, unknowns, and perspectives. In: *Ocean Acidification* [Gattuso, J.-P. and L. Hansson (eds.)]. Oxford University Press, Oxford, UK, pp. 291-311.

Genner, M.J., D.W. Sims, A.J. Southward, G.C. Budd, P. Masterson, M. McHugh, P. Rendle, E.J. Southall, V.J. Wearmouth, and S.J. Hawkins, 2010: Body size-dependent responses of a marine fish assemblage to climate change and fishing over a century-long scale. *Global Change Biology*, **16**(**2**), 517-527.

Geresi, E., R. Chapman, T. McGee, and B. Woolsey, 2009: Monitoring seafloor instability caused by the presence of gas hydrate using ocean acoustical and geophysical techniques in the northern Gulf of Mexico. In: *Natural Gas Hydrates – Energy Resource Potential and Associated Geologic Hazards* [Collett, T., A. Johnson, C. Knapp, and R. Boswell (eds.)]. AAPG Memoir 89, Co-Published by The American Association of Petroleum Geologists (AAPG), Energy Minerals Division, with the U.S. Department of Energy, National Energy Technology Laboratory (NETL), and the AAPG Foundation, AAPG, Tulsa, OK, USA, pp. 287-296.

Gillett, N.P. and P.A. Stott, 2009: Attribution of anthropogenic influence on seasonal sea level pressure. *Geophysical Research Letters*, **36**(**23**), L23709, doi:10.1029/2009GL041269.

Gillett, N.P., F.W. Zwiers, A.J. Weaver, and P.A. Stott, 2003: Detection of human influence on sea-level pressure. *Nature*, **422**(**6929**), 292-294.

Gilman, E., J. Ellison, and R. Coleman, 2007: Assessment of mangrove response to projected relative sea-level rise and recent historical reconstruction of shoreline position. *Environmental Monitoring and Assessment*, **124**(**1-3**), 105-130.

Gleckler, P.J., B. Santer, C. Domingues, D. Pierce, T. Barnett, J. Church, K. Taylor, K. AchutaRao, T. Boyer, and M. Ishii, 2012: Human-induced global ocean warming on multidecadal timescales. *Nature Climate Change*, **2**, 524-529.

Gledhill, D.K., R. Wanninkhof, F.J. Millero, and M. Eakin, 2008: Ocean acidification of the Greater Caribbean Region 1996-2006. *Journal of Geophysical Research*, **113**(**C10**), C10031, doi:10.1029/2007JC004629.

Glynn, P.W., 1984: Widespread coral mortality and the 1982-83 El Niño warming event. *Environmental Conservation*, **11**(**2**), 133-146.

Glynn, P.W., 2001: Eastern Pacific coral reef ecosystems. In: *Coastal Marine Ecosystems of Latin America* [Seeliger, U. and B. Kjerfve (eds.)]. Ecological Studies, Vol. 144, Springer-Verlag, Berlin, Germany, pp. 281-305.

Glynn, P.W., 2011: In tandem reef coral and cryptic metazoan declines and extinctions. *Bulletin of Marine Science*, **87**(**4**), 767-794.

Gómez-Gesteira, M., M. De Castro, I. Álvarez, M.N. Lorenzo, J.L.G. Gesteira, and A.J.C. Crespo, 2008: Spatio-temporal upwelling trends along the Canary Upwelling System (1967-2006). *Annals of the New York Academy of Sciences*, **1146**(**1**), 320-337.

González-Taboada, F. and R. Anadón, 2012: Patterns of change in sea surface temperature in the North Atlantic during the last three decades: beyond mean trends. *Climatic Change*, **115(2)**, 419-431.

Goreau, T., T. McClanahan, R. Hayes, and A. Strong, 2000: Conservation of coral reefs after the 1998 global bleaching event. *Conservation Biology*, **14**(**1**), 5-15.

Graham, N.A., S.K. Wilson, S. Jennings, N.V. Polunin, J. Robinson, J.P. Bijoux, and T.M. Daw, 2007: Lag effects in the impacts of mass coral bleaching on coral reef fish, fisheries, and ecosystems. *Conservation Biology*, **21**(**5**), 1291-1300.

Graham, N.A., T.R. McClanahan, M.A. MacNeil, S.K. Wilson, N.V. Polunin, S. Jennings, P. Chabanet, S. Clark, M.D. Spalding, Y. Letourneur, L. Bigot, R. Galzin, M.C. Öhman, K.C. Garpe, A.J. Edwards, and C.R. Sheppard, 2008: Climate warming, marine protected areas and the ocean-scale integrity of coral reef ecosystems. *PLoS ONE*, **3**(**8**), e3039, doi:10.1371/journal.pone.0003039.

Grantham, B.A., F. Chan, K.J. Nielsen, D.S. Fox, J.A. Barth, A. Huyer, J. Lubchenco, and B.A. Menge, 2004: Upwelling-driven nearshore hypoxia signals ecosystem and oceanographic changes in the northeast Pacific. *Nature*, **429**(**6993**), 749-754.

Green, D., L. Alexander, K. McInnes, J. Church, N. Nicholls, and N. White, 2010: An assessment of climate change impacts and adaptation for the Torres Strait Islands, Australia. *Climatic Change*, **102**(**3-4**), 405-433.

Gregg, W.W., N.W. Casey, and C.R. McClain, 2005: Recent trends in global ocean chlorophyll. *Geophysical Research Letters*, **32**(**3**), L03606, doi:10.1029/2004GL021808.

Griffith, G.P., E.A. Fulton, R. Gorton, and A.J. Richardson, 2012: Predicting interactions among fishing, ocean warming, and ocean acidification in a marine system with whole-ecosystem models. *Conservation Biology*, **26**(**6**), 1145-1152.

Gruber, N., 2011: Warming up, turning sour, losing breath: ocean biogeochemistry under global change. *Philosophical Transactions of the Royal Society A*, **369**(**1943**), 1980-1996.

Gruber, N., C. Hauri, Z. Lachkar, D. Loher, T.L. Frölicher, and G.K. Plattner, 2012: Rapid progression of ocean acidification in the California Current System. *Science*, **337**(**6091**), 220-223.

Guilyardi, E., H. Bellenger, M. Collins, S. Ferrett, W. Cai, and A. Wittenberg, 2012: A first look at ENSO in CMIP5. *CLIVAR Exchanges No.58*, **17**(**1**), 29-32.

Guinotte, J.M., J. Orr, S. Cairns, A. Freiwald, L. Morgan, and R. George, 2006: Will human-induced changes in seawater chemistry alter the distribution of deep-sea scleractinian corals? *Frontiers in Ecology and the Environment*, **4**(**3**), 141-146.

Gutiérrez, D., I. Bouloubassi, A. Sifeddine, S. Purca, K. Goubanova, M. Graco, D. Field, L. Méjanelle, F. Velazco, A. Lorre, R. Salvatteci, D. Quispe, G. Vargas, B. Dewitte, and L. Ortlieb, 2011: Coastal cooling and increased productivity in the main upwelling zone off Peru since the mid-twentieth century. *Geophysical Research Letters*, **38**, L07603, doi:10.1029/2010GL046324.

Hall-Spencer, J.M., R. Rodolfo-Metalpa, S. Martin, E. Ransome, M. Fine, S.M. Turner, S.J. Rowley, D. Tedesco, and M.-C. Buia, 2008: Volcanic carbon dioxide vents show ecosystem effects of ocean acidification. *Nature*, **454**(**7200**), 96-99.

Halpern, B.S., K.L. McLeod, A.A. Rosenberg, and L.B. Crowder, 2008: Managing for cumulative impacts in ecosystem-based management through ocean zoning. *Ocean & Coastal Management*, **51**(**3**), 203-211.

Halpern, B.S., C.M. Ebert, C.V. Kappel, E.M.P. Madin, F. Micheli, M. Perry, K.A. Selkoe, and S. Walbridge, 2009: Global priority areas for incorporating land-sea connections in marine conservation. *Conservation Letters*, **2**(**4**), 189-196.

Halpern, B.S., S.E. Lester, and K.L. McLeod, 2010: Placing marine protected areas onto the ecosystem-based management seascape. *Proceedings of the National Academy of Sciences of the United States of America*, **107**(**43**), 18312-18317.

Hänninen, J. and I. Vuorinen, 2011: Time-varying parameter analysis of the Baltic Sea freshwater runoffs. *Environmental Modeling & Assessment*, **16**(**1**), 53-60.

Hare, S.R. and N.J. Mantua, 2000: Empirical evidence for North Pacific regime shifts in 1977 and 1989. *Progress in Oceanography*, **47**(**2-4**), 103-145.

Harley, C.D., 2011: Climate change, keystone predation, and biodiversity loss. *Science*, **334**(**6059**), 1124-1127.

Harvell, C.D., K. Kim, J.M. Burkholder, R.R. Colwell, P.R. Epstein, D.J. Grimes, E.E. Hofmann, E.K. Lipp, A.D. Osterhaus, R.M. Overstreet, J.W. Porter, G.W. Smith, and G.R. Vasta, 1999: Emerging marine diseases-climate links and anthropogenic factors. *Science*, **285**(**5433**), 1505-1510.

Harvell, C.D., C.E. Mitchell, J.R. Ward, S. Altizer, A.P. Dobson, R.S. Ostfeld, and M.D. Samuel, 2002: Climate warming and disease risks for terrestrial and marine biota. *Science*, **296**(**5576**), 2158-2162.

Harvell, D., R. Aronson, N. Baron, J. Connell, A. Dobson, S. Ellner, L. Gerber, K. Kim, A. Kuris, H. McCallum, K. Lafferty, B. McKay, J. Porter, M. Pascual, G. Smith, K. Sutherland, and J. Ward, 2004: The rising tide of ocean diseases: unsolved problems and research priorities. *Frontiers in Ecology and the Environment*, **2**(**7**), 375-382.

Hashioka, T., T.T. Sakamoto, and Y. Yamanaka, 2009: Potential impact of global warming on North Pacific spring blooms projected by an eddy-permitting 3-D ocean ecosystem model. *Geophysical Research Letters*, **36**, L20604, doi:10.1029/2009GL038912.

Hátún, H., M. Payne, G. Beaugrand, P. Reid, A. Sandø, H. Drange, B. Hansen, J. Jacobsen, and D. Bloch, 2009: Large bio-geographical shifts in the north-eastern Atlantic Ocean: from the subpolar gyre, via plankton, to blue whiting and pilot whales. *Progress in Oceanography*, **80**(**3-4**), 149-162.

Hazen, E.L., S. Jorgensen, R.R. Rykaczewski, S.J. Bograd, D.G. Foley, I.D. Jonsen, S.A. Shaffer, J.P. Dunne, D.P. Costa, and L.B. Crowder, 2012: Predicted habitat shifts of Pacific top predators in a changing climate. *Nature Climate Change*, **3**, 234-238.

Head, E.J.H. and P. Pepin, 2010: Monitoring changes in phytoplankton abundance and composition in the Northwest Atlantic: a comparison of results obtained by continuous plankton recorder sampling and colour satellite imagery. *Journal of Plankton Research*, **32**(**12**), 1649-1660.

Healy, T. and K. Harada, 1991: Definition and physical characteristics of the world's enclosed coastal seas. *Marine Pollution Bulletin*, **23**, 639-644.

Hegerl, G.C., F.W. Zwiers, P. Braconnot, N.P. Gillett, Y. Luo, J.A. Marengo Orsini, N. Nicholls, J.T. Penner, and P. Stott, 2007: Understanding and attributing climate change. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 643-745.

Hegerl, G.C., O. Hoegh-Guldberg, G. Casassa, M.P. Hoerling, R.S. Kovats, C. Parmesan, D.W. Pierce, and P.A. Stott, 2010: Good practice guidance paper on detection and attribution related to anthropogenic climate change. In: *Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Detection and Attribution of Anthropogenic Climate Change* [Stocker, T.F., C.B. Field, D. Qin, V. Barros, G.-K. Plattner, M. Tignor, P.M. Midgley, and K.L. Ebi (eds.)]. IPCC Working Group I Technical Support Unit, University of Bern, Bern, Switzerland, 8 pp.

Heil, C.A., P.M. Glibert, M.A. Al-Sarawi, M. Faraj, M. Behbehani, and M. Husain, 2001: First record of a fish-killing *Gymnodinium* sp. bloom in Kuwait Bay, Arabian Sea: chronology and potential causes. *Marine Ecology Progress Series*, **214**, 15-23.

Heiss, G.A., 1996: Annual band width variation in *Porites* sp. from Aqaba, Gulf of Aqaba, Red Sea. *Bulletin of Marine Science*, **59**(**2**), 393-403.

Heitmann, N. and S. Khalilian, 2010: *Accounting for CO_2 Emissions from International Shipping: Burden Sharing Under Different UNFCCC Allocation Options and Regime Scenarios*. Kiel Working Paper No. 1655, Kiel Institute for the World Economy, Kiel, Germany, 36 pp.

Helly, J.J. and L.A. Levin, 2004: Global distribution of naturally occurring marine hypoxia on continental margins. *Deep-Sea Research Part I: Oceanographic Research Papers*, **51**(**9**), 1159-1168.

Helm, K.P., N.L. Bindoff, and J.A. Church, 2011: Observed decreases in oxygen content of the global ocean. *Geophysical Research Letters*, **38**(**23**), L23602, doi:10.1029/2011GL049513.

Henriksen, P., 2009: Long-term changes in phytoplankton in the Kattegat, the Belt Sea, the Sound and the western Baltic Sea. *Journal of Sea Research*, **61**(**1-2**), 114-123.

Henson, S.A., J.L. Sarmiento, J.P. Dunne, L. Bopp, I.D. Lima, S.C. Doney, J. John, and C. Beaulieu, 2010: Detection of anthropogenic climate change in satellite records of ocean chlorophyll and productivity. *Biogeosciences*, **7**, 621-640.

Hermansen, Ø. and K. Heen, 2012: Norwegian salmonid farming and global warming: socioeconomic impacts. *Aquaculture Economics & Management*, **16**(**3**), 220-221.

Hermant, M., J. Lobry, S. Bonhommeau, J.C. Poulard, and O. Le Pape, 2010: Impact of warming on abundance and occurrence of flatfish populations in the Bay of Biscay (France). *Journal of Sea Research*, **64**(**1-2**), 45-53.

Heymans, J.J., L.J. Shannon, and A. Jarre, 2004: Changes in the northern Benguela ecosystem over three decades: 1970s, 1980s, and 1990s. *Ecological Modelling*, **172**(**2-4**), 175-195.

Hickey, B.M., 1979: The California Current System – hypotheses and facts. *Progress in Oceanography*, **8**(**4**), 191-279.

Hiddink, J.G. and R. ter Hofstede, 2008: Climate induced increases in species richness of marine fishes. *Global Change Biology*, **14**(**3**), 453-460.

Hilborn, R., 2007: Defining success in fisheries and conflicts in objectives. *Marine Policy*, **31**(**2**), 153-158.

Hill, K.L., S.R. Rintoul, R. Coleman, and K.R. Ridgway, 2008: Wind forced low frequency variability of the East Australia Current. *Geophysical Research Letters*, **35**(**8**), L08602, doi:10.1029/2007GL032912.

Hilmi, N., D. Allemand, S. Dupont, A. Safa, G. Haraldsson, P.A.L.D. Nunes, C. Moore, C. Hattam, S. Reynaud, J.M. Hall-Spencer, M. Fine, C. Turley, R. Jeffree, J. Orr, P.L. Munday, and S.R. Cooley, 2013: Towards improved socio-economic assessments of ocean acidification's impacts. *Marine Biology*, **160(8)**, 1773-1787.

Hitchcock, G.L., P. Lane, S. Smith, J.G. Luo, and P.B. Ortner, 2002: Zooplankton spatial distributions in coastal waters of the northern Arabian Sea, August, 1995. *Deep-Sea Research Part II: Topical Studies in Oceanography*, **49**(**12**), 2403-2423.

Hjort, J., 1914: Fluctuations in the great fisheries of Northern Europe. *Rapports et Procès-Verbaux des Reunions du Conseil Permanent International pour l'Exploration de la Mer (CIEM) [International Council for the Exploration of the Sea (ICES)]*, **20**, 1-228.

Hoegh-Guldberg, O., 1999: Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research*, **50**(**8**), 839-866.

Hoegh-Guldberg, O., 2011: Coral reef ecosystems and anthropogenic climate change. *Regional Environmental Change*, **11(1 Suppl.)**, S215-S227.

Hoegh-Guldberg, O., 2012: The adaptation of coral reefs to climate change: is the Red Queen being outpaced? *Scientia Marina*, **76**(**2**), 403-408.

Hoegh-Guldberg, O. and J.F. Bruno, 2010: The impact of climate change on the world's marine ecosystems. *Science*, **328**(**5985**), 1523-1528.

Hoegh-Guldberg, O. and B. Salvat, 1995: Periodic mass-bleaching and elevated sea temperatures – bleaching of outer reef slope communities in Moorea, French Polynesia. *Marine Ecology Progress Series*, **121**(**1-3**), 181-190.

Hoegh-Guldberg, O., P.J. Mumby, A.J. Hooten, R.S. Steneck, P. Greenfield, E. Gomez, C.D. Harvell, P.F. Sale, A.J. Edwards, K. Caldeira, N. Knowlton, C.M. Eakin, R. Iglesias-Prieto, N. Muthiga, R.H. Bradbury, A. Dubi, and M.E. Hatziolos, 2007: Coral reefs under rapid climate change and ocean acidification. *Science*, **318**(**5857**), 1737-1742.

Hoegh-Guldberg, O., L. Hughes, S. McIntyre, D.B. Lindenmayer, C. Parmesan, H.P. Possingham, and C.D. Thomas, 2008: Assisted colonization and rapid climate change. *Science*, **321**(**5887**), 345-346.

Hoegh-Guldberg, O., H. Hoegh-Guldberg, J.E.N. Veron, A. Green, E.D. Gomez, J.M. Lough, M. King, A. Ambariyanto, L. Hansen, J.E. Cinner, G. Dews, G. Russ, H.Z. Shuttenberg, E.L. Penaflor, C.M. Eakin, T.R.L. Christiensen, M. Abbey, F. Areki, R.A. Kosaka, A. Tewfik, and J. Oliver, 2009: *The Coral Triangle and Climate Change: Ecosystems, People and Societies at Risk*. World Wide Fund For Nature (WWF) Australia, Brisbane, QLD, Australia, 276 pp.

Hoegh-Guldberg, O., S. Andréfouët, K.E. Fabricius, G. Diaz-Pulido, J.M. Lough, P.A. Marshall, and M.S. Pratchett, 2011a: Vulnerability of coral reefs in the tropical Pacific to climate change. In: *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change* [Bell, J.D., J.E. Johnson, and A.J. Hobday (eds.)]. Secretariat of the Pacific Community, Noumea, New Caledonia. pp. 251-296.

Hoegh-Guldberg, O., G. Hegerl, T. Root, F. Zwiers, P. Stott, D. Pierce, and M. Allen, 2011b: Correspondence: difficult but not impossible. *Nature Climate Change*, **1**(**2**), 72, doi:10.1038/nclimate1107.

Hoegh-Guldberg, O., T. Aqorau, R. Arnason, T. Chansiri, N. Del Rio, H. Demone, S. Earle, M.H. Feeley, D. Gutierrez, R. Hilborn, N. Ishil, C. Lischewski, J. Lubchenco, K. Anh Nguyen, D. Obura, H.E.R. Payet, T. Neroni Slade, J. Tanzer, J.H. Williams, D.J. Wright, and J. Xu, 2013: *Indispensable Ocean: Aligning Ocean Health and Human Well-Being – Guidance from the Blue Ribbon Panel to the Global Partnership for Oceans*. Working Paper Report No. 82651, The World Bank, Washington, DC USA, 40 pp.

Hofmann, A.F., E.T. Peltzer, and P.G. Brewer, 2013: Kinetic bottlenecks to respiratory exchange rates for deep-sea – Part I: Oxygen. *Biogeosciences*, **10**, 5049-5060.

Hönisch, B., A. Ridgwell, D.N. Schmidt, E. Thomas, S.J. Gibbs, A. Sluijs, R.E. Zeebe, L. Kump, R.C. Martindale, S.E. Greene, W. Kiessling, J. Ries, J.C. Zachos, D.L. Royer, S. Barker, T.M. Marchitto Jr., R. Moyer, C. Pelejero, P. Zivera, G.L. Foster, and B. Williams, 2012: The geological record of ocean acidification. *Science*, **335**(**6072**), 1058-1063.

Hosoda, S., T. Suga, N. Shikama, and K. Mizuno, 2009: Global surface layer salinity change detected by Argo and its implication for hydrological cycle intensification. *Journal of Oceanography*, **65**, 579-586.

Howard, J.A., A. Jarre, A. Clark, and C. Moloney, 2007: Application of the sequential t-test algorithm for analysing regime shifts to the southern Benguela ecosystem. *African Journal of Marine Science*, **29**(**3**), 437-451.

Howell, E.A., C.C.C. Wabnitz, J.P. Dunne, and J.J. Polovina, 2013: Climate-induced primary productivity change and fishing impacts on the Central North Pacific ecosystem and Hawaii-based pelagic longline fishery. *Climatic Change*, **119**(**1**), 79-93.

Hughes, T.P., 1994: Catastrophes, phase shifts, and large-scale degradation of a Caribbean coral reef. *Science*, **265**(**5178**), 1547-1551.

Hughes, T.P., A.H. Baird, D.R. Bellwood, M. Card, S.R. Connolly, C. Folke, R. Grosberg, O. Hoegh-Guldberg, J.B. Jackson, J. Kleypas, J.M. Lough, P. Marshall, M. Nystrom, S.R. Palumbi, J.M. Pandolfi, B. Rosen, and J. Roughgarden, 2003: Climate change, human impacts, and the resilience of coral reefs. *Science*, **301**(**5635**), 929-933.

Hughes, T.P., D.R. Bellwood, A.H. Baird, J. Brodie, J.F. Bruno, and J.M. Pandolfi, 2011: Shifting base-lines, declining coral cover, and the erosion of reef resilience: comment on Sweatman et al. (2011). *Coral Reefs*, **30**(**3**), 653-660.

Hunt, G.L., P. Stabeno, G. Walters, E. Sinclair, R.D. Brodeur, J.M. Napp, and N.A. Bond, 2002: Climate change and control of the southeastern Bering Sea pelagic ecosystem. *Deep-Sea Research Part II: Topical Studies in Oceanography*, **49**(**26**), 5821-5853.

Hunt, G.L., B.M. Allen, R.P. Angliss, T. Baker, N. Bond, G. Buck, G.V. Byrd, K.O. Coyle, A. Devol, D.M. Eggers, L. Eisner, R.A. Feely, S. Fitzgerald, L.W. Fritz, E.V. Gritsay, C. Ladd, W. Lewis, J.T. Mathis, C.W. Mordy, F. Mueter, J. Napp, E. Sherr, D. Shull, P. Stabeno, M.A. Stephanenko, S. Strom, and T.E. Whitledge, 2010: Status and trends of the Bering Sea region, 2003-2008. In: *Marine Ecosystems of the North Pacific Ocean, 2003-2008* [McKinnell, S.M. and M.J. Dagg (eds.)]. PICES Special Publication No. 4, North Pacific Marine Science Organization (PICES), Sydney, BC, Canada, pp. 196-267.

Huse, G. and I. Ellingsen, 2008: Capelin migrations and climate change – a modelling analysis. *Climatic Change*, **87**(**1**), 177-197.

Huse, G., J.C. Holst, K. Utne, L. Nøttestad, W. Melle, A. Slotte, G. Ottersen, T. Fenchel, and F. Uiblein, 2012: Effects of interactions between fish populations on ecosystem dynamics in the Norwegian Sea – results of the INFERNO project. *Marine Biology Research*, **8**(**5-6**), 415-419.

Hutchings, L., C.D. van der Lingen, L.J. Shannon, R.J.M. Crawford, H.M.S. Verheye, C.H. Bartholomae, A.K. van der Plas, D. Louw, A. Kreiner, M. Ostrowski, Q. Fidel, R.G. Barlow, T. Lamont, J. Coetzee, F. Shillington, J. Veitch, J.C. Currie, and P.M.S. Monteiro, 2009: The Benguela Current: an ecosystem of four components. *Progress in Oceanography*, **83**(**1-4**), 15-32.

ICES, 2012: Book 3: The Barents Sea and the Norwegian Sea. In: *ICES Advice 2012, Books 1-10.* Report of the ICES Advisory Committee 2012, International Council for the Exploration of the Sea (ICES), Copenhagen, Denmark, 79 pp.

Iles, A.C., T.C. Gouhier, B.A. Menge, J.S. Stewart, A.J. Haupt, and M.C. Lynch, 2012: Climate-driven trends and ecological implications of event-scale upwelling in the California Current System. *Global Change Biology*, **18**(**2**), 783-796.

IPCC, 2005: *IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change (IPCC)* [Metz, B., O. Davidson, H.C. de Coninck, M. Loos, and L.A. Meyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 442 pp.

IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 582 pp.

Irvine, J.R. and M.A. Fukuwaka, 2011: Pacific salmon abundance trends and climate change. *International Council for the Exploration of the Sea (ICES) Journal of Marine Science*, **68**(**6**), 1122-1130.

Ito, S., H. Sugisaki, A. Tsuda, O. Yamamura, and K. Okuda, 2004: Contributions of the VENFISH program: meso-zooplankton, Pacific saury (*Cololabis saira*) and walleye pollock (*Theragra chalcogramma*) in the northwestern Pacific. *Fisheries Oceanography*, **13**(**Suppl. s1**), 1-9.

Ito, S., K.A. Rose, A.J. Miller, K. Drinkwater, K. Brander, J.E. Overland, S. Sundby, E. Curchitser, J.W. Hurrell, and Y. Yamanaka, 2010: Ocean ecosystem responses to future global change scenarios: a way forward. In: *Marine Ecosystems and Global Change* [Barange, M., J.G. Field, R.H. Harris, E. Hofmann, R.I. Perry, and F. Werner (eds.)]. Oxford University Press, Oxford, UK, pp. 287-322.

Ittekkot, V., S. Jilan, E. Miles, E. Desa, B.N. Desai, J.T. Everett, J.J. Magnuson, A. Tsyban, and S. Zuta, 1996: Oceans. In: *Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analyses. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change* [Watson, R.T., M. Zinyowera, and R. Moss (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 267-288.

Iversen, T., 1934: Some observations on cod in northern waters. In: *Report on Norwegian Fishery and Marine Investigations, Vol.4 No. 8*. Norwegian Directorate of Fisheries and John Griegs Boktrykkeri, Bergen, Norway, pp. 1-35, brage.bibsys.no/xmlui/bitstream/handle/11250/114626/1/sh_vol04_08_1934.pdf.

Jenkins, W.J., 2008: The biogeochemical consequences of changing ventilation in the Japan/East Sea. *Marine Chemistry*, **108**(**3-4**), 137-147.

Jin, M.B., C. Deal, J. Wang, and C.P. McRoy, 2009: Response of lower trophic level production to long-term climate change in the southeastern Bering Sea. *Journal of Geophysical Research*, **114**, C04010, doi:10.1029/2008JC005105.

Johannesen, E., R.B. Ingvaldsen, B. Bogstad, P. Dalpadado, E. Eriksen, H. Gjøsæter, T. Knutsen, M. Skern-Mauritzen, and J.E. Stiansen, 2012: Changes in Barents Sea ecosystem state, 1970-2009: climate fluctuations, human impact, and trophic interactions. *International Council for the Exploration of the Sea (ICES) Journal of Marine Science*, **69**(**5**), 880-889.

Jordà, G., D. Gomis, E. Alvarez-Fanjul, and S. Somot, 2012: Atmospheric contribution to Mediterranean and nearby Atlantic sea level variability under different climate change scenarios. *Global and Planetary Change*, **80-81**, 198-214.

Jung, S., 2008: Spatial variability in long-term changes of climate and oceanographic conditions in Korea. *Journal of Environmental Biology*, **29**(**4**), 519-529.

Jung, S., I.-C. Pang, J.-H. Lee, I. Choi, and H.K. Cha, 2014: Latitudinal shifts in the distribution of exploited fishes in Korean waters during the last 30 years: a consequence of climate change. *Reviews in Fisheries Biology and Fisheries*, **24**, 443-462, doi:10.1007/s11160-013-9310-1.

Jury, M., T. McClanahan, and J. Maina, 2010: West Indian Ocean variability and East African fish catch. *Marine Environmental Research*, **70**(**2**), 162-170.

Justić, D., N.N. Rabalais, and R.E. Turner, 1996: Effects of climate change on hypoxia in coastal waters: a doubled CO_2 scenario for the northern Gulf of Mexico. *Limnology and Oceanography*, **41**(**5**), 992-1003.

Justić, D., V.J. Bierman, D. Scavia, and R.D. Hetland, 2007: Forecasting Gulf's hypoxia: the next 50 years? *Estuaries and Coasts*, **30**(**5**), 791-801.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, A. Leetmaa, R. Reynolds, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K.C. Mo, C. Ropelewski, J. Wang, R. Jenne, and D. Joseph, 1996: The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society*, **77**(**3**), 437-471.

Kane, J., 2007: Zooplankton abundance trends on Georges Bank, 1977-2004. *International Council for the Exploration of the Sea (ICES) Journal of Marine Science*, **64**(**5**), 909-919.

Karstensen, J., L. Stramma, and M. Visbeck, 2008: Oxygen minimum zones in the eastern tropical Atlantic and Pacific oceans. *Progress in Oceanography*, **77**(**4**), 331-350.

Kaye, S., 2012: Climate change and maritime security. In: *Climate Change and the Oceans: Gauging the Legal and Policy Currents in the Asia Pacific and Beyond* [Warner, R. and C. Schofield (eds.)]. Edward Elgar Publishing, Cheltenham, UK and Northampton, MA, USA, pp. 153-166.

Keeling, R.E., A. Körtzinger, and N. Gruber, 2010: Ocean deoxygenation in a warming world. *Annual Review of Marine Science*, **2**, 199-229.

Keister, J.E., E. Di Lorenzo, C.A. Morgan, V. Combes, and W.T. Peterson, 2011: Zooplankton species composition is linked to ocean transport in the Northern California Current. *Global Change Biology*, **17**(**7**), 2498-2511.

Kelly, R.P., M.M. Foley, W.S. Fisher, R.A. Feely, B.S. Halpern, G.G. Waldbusser, and R.R. Caldwell, 2011: Mitigating local causes of ocean acidification with existing laws. *Science*, **332**(**6033**), 1036-1037.

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

Kerr, R.A., 2000: A North Atlantic climate pacemaker for the centuries. *Science*, **288**(**5473**), 1984-1985.

Kessler, J.D., D.L. Valentine, M.C. Redmond, M. Du, E.W. Chan, S.D. Mendes, E.W. Quiroz, C.J. Villanueva, S.S. Shusta, L.M. Werra, S.A. Yvon-Lewis, and T.C. Weber, 2011: A persistent oxygen anomaly reveals the fate of spilled methane in the deep Gulf of Mexico. *Science*, **331**(**6015**), 312-315.

Key, R.M., A. Kozyr, C.L. Sabine, K. Lee, R. Wanninkhof, J.L. Bullister, R.A. Feely, F.J. Millero, C.W. Mordy, and T.H. Peng, 2004: A global ocean carbon climatology: results from Global Data Analysis Project (GLODAP). *Global Biogeochemical Cycles*, **18**(**4**), GB4031, doi:10.1029/2004GB002247.

Kideys, A.E., 2002: Fall and rise of the Black Sea ecosystem. *Science*, **297**(**5586**), 1482-1484.

King, J.R., V.N. Agostini, C.J. Harvey, G.A. McFarlane, M.G.G. Foreman, J.E. Overland, E. Di Lorenzo, N.A. Bond, and K.Y. Aydin, 2011: Climate forcing and the California Current ecosystem. *International Council for the Exploration of the Sea (ICES) Journal of Marine Science*, **68**(**6**), 1199-1216.

Kirby, R.R. and G. Beaugrand, 2009: Trophic amplification of climate warming. *Proceedings of the Royal Society B*, **276**(**1676**), 4095-4103.

Kirkman, S.P., D. Yemane, J. Kathena, S.K. Mafwila, S.E. Nsiangango, T. Samaai, B. Axelsen, and L. Singh, 2013: Identifying and characterizing demersal fish biodiversity hotspots in the Benguela Current Large Marine Ecosystem: relevance in the light of global changes. *International Council for the Exploration of the Sea (ICES) Journal of Marine Science*, **70(5)**, 943-954.

Kleypas, J.A., R.W. Buddemeier, D. Archer, J.-P. Gattuso, C. Langdon, and B.N. Opdyke, 1999: Geochemical consequences of increased atmospheric carbon dioxide on coral reefs. *Science*, **284**(**5411**), 118-120.

Knoll, A.H. and W.W. Fischer, 2011: Skeletons and ocean chemistry: the long view. In: *Ocean Acidification* [Gattuso, J.-P. and L. Hansson (eds.)]. Oxford University Press, Oxford, UK, pp. 67-82.

Knutson, T.R., J.L. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, I. Held, J.P. Kossin, A. Srivastava, and M. Sugi, 2010: Tropical cyclones and climate change. *Nature Geoscience*, **3**(**3**), 157-163.

Koslow, J.A., R. Goericke, A. Lara-Lopez, and W. Watson, 2011: Impact of declining intermediate-water oxygen on deepwater fishes in the California Current. *Marine Ecology Progress Series*, **436**, 207-218.

Krishnan, P., S.D. Roy, G. George, R.C. Srivastava, A. Anand, S. Murugesan, M. Kaliyamoorthy, N. Vikas, and R. Soundararajan, 2011: Elevated sea surface temperature during May 2010 induces mass bleaching of corals in the Andaman. *Current Science*, **100**(**1**), 111-117.

Kroeker, K.J., R.L. Kordas, R. Crim, I.E. Hendriks, L. Ramajo, G.S. Singh, C.M. Duarte, and J.-P. Gattuso, 2013: Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. *Global Change Biology*, **19(6)**, 1884-1896.

Kurien, J. and R. Willmann, 2009: Special considerations for small-scale fisheries management in developing countries. In: *A Fishery Manager's Guidebook* [Cochrane, K. and S.M. Garcia (eds.)]. Food and Agricultural Organization of the United Nations (FAO), Rome, Italy and Wiley-Blackwell, Chichester, UK, pp. 404-424.

Kuzmina, S.I., L. Bengtsson, O.M. Johannessen, H. Drange, L.P. Bobylev, and M.W. Miles, 2005: The North Atlantic Oscillation and greenhouse-gas forcing. *Geophysical Research Letters*, **32**(**4**), L04703, doi:10.1029/2004GL021064.

Laffoley, D. and G.D. Grimsditch (eds.), 2009: *The Management of Natural Coastal Carbon Sinks*. International Union for Conservation of Nature and Natural Resources (IUCN), Gland, Switzerland, 53 pp.

Last, P.R., W.T. White, D.C. Gledhill, A.J. Hobday, R. Brown, G.J. Edgar, and G. Pecl, 2011: Long-term shifts in abundance and distribution of a temperate fish fauna: a response to climate change and fishing practices. *Global Ecology and Biogeography*, **20**(**1**), 58-72.

Laws, E.A., P.G. Falkowski, W.O. Smith, H. Ducklow, and J.J. McCarthy, 2000: Temperature effects on export production in the open ocean. *Global Biogeochemical Cycles*, **14**(**4**), 1231-1246.

Le Borgne, R., R.T. Barber, T. Delcroix, H.Y. Inoue, D.J. Mackey, and M. Rodier, 2002: Pacific warm pool and divergence: temporal and zonal variations on the equator and their effects on the biological pump. *Deep-Sea Research Part II: Topical Studies in Oceanography*, **49**(**13-14**), 2471-2512.

Le Borgne, W.R., V. Allain, S.P. Griffiths, R.J. Matear, A.D. McKinnon, A.J. Richardson, and J.W. Young, 2011: Vulnerability of open oceans food webs in the tropical Pacific to climate change. In: *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change* [Bell, J.D., J.E. Johnson, and A.J. Hobday (eds.)]. Secretariat of the Pacific Community, Noumea, New Caledonia, pp. 189-250.

Leduc, G., C.T. Herbert, T. Blanz, P. Martinez, and R. Schneider, 2010: Contrasting evolution of sea surface temperature in the Benguela upwelling system under natural and anthropogenic climate forcings. *Geophysical Research Letters*, **37**(**20**), L20705, doi:10.1029/2010GL044353.

Lee, S.-K., W. Park, E. van Sebille, M.O. Baringer, C. Wang, D.B. Enfield, S.G. Yeager, and B.P. Kirtman, 2011: What caused the significant increase in Atlantic Ocean heat content since the mid-20th century? *Geophysical Research Letters*, **38**(**17**), L17607, doi:10.1029/2011GL048856.

Lee, S.-S., J.-Y. Lee, B. Wang, K.-J. Ha, K.-Y. Heo, F.-F. Jin, D.M. Straus, and J. Shukla, 2012: Interdecadal changes in the storm track activity over the North Pacific and North Atlantic. *Climate Dynamics*, **39**(**1-2**), 313-327.

Lee, T. and M.J. McPhaden, 2010: Increasing intensity of El Niño in the central-equatorial Pacific. *Geophysical Research Letters*, **37(14)**, L14603, doi:10.1029/2010GL044007.

Lee, Z., S. Shang, C. Hu, M. Lewis, R. Arnone, Y. Li, and B. Lubac, 2010: Time series of bio-optical properties in a subtropical gyre: implications for the evaluation of interannual trends of biogeochemical properties. *Journal of Geophysical Research*, **115(C9)**, C09012, doi:10.1029/2009JC005865.

Lehodey, P., M. Bertignac, J. Hampton, A. Lewis, and J. Picaut, 1997: El Niño Southern Oscillation and tuna in the western Pacific. *Nature*, **389**(**6652**), 715-718.

Lehodey, P., J. Alheit, M. Barange, T. Baumgartner, G. Beaugrand, K. Drinkwater, J.M. Fromentin, S.R. Hare, G. Ottersen, R.I. Perry, C. Roy, C.D. van der Lingen, and F. Werner, 2006: Climate variability, fish, and fisheries. *Journal of Climate*, **19**(**20**), 5009-5030.

Lehodey, P., I. Senina, and R. Murtugudde, 2008: A spatial ecosystem and populations dynamics model (SEAPODYM) – modeling of tuna and tuna-like populations. *Progress in Oceanography*, **78**(**4**), 304-318.

Lehodey, P., R. Murtugudde, and I. Senina, 2010a: Bridging the gap from ocean models to population dynamics of large marine predators: a model of mid-trophic functional groups. *Progress in Oceanography*, **84**(**1-2**), 69-84.

Lehodey, P., I. Senina, J. Sibert, L. Bopp, B. Calmettes, J. Hampton, and R. Murtugudde, 2010b: Preliminary forecasts of Pacific bigeye tuna population trends under the A2 IPCC scenario. *Progress in Oceanography*, **86**, 302-315.

Lehodey, P., J. Hampton, R.W. Brill, S. Nicol, I. Senina, B. Calmettes, H.-O. Pörtner, L. Bopp, T. Ilyina, J.D. Bell, and J. Sibert, 2011: Vulnerability of the ocean fisheries in the tropical Pacific to climate change. In: *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change* [Bell, J.D., J.E. Johnson, and A.J. Hobday (eds.)]. Secretariat of the Pacific Community, Noumea, New Caledonia, pp. 433-492.

Lehodey, P., I. Senina, B. Calmettes, J. Hampton, and S. Nicol, 2013: Modelling the impact of climate change on Pacific skipjack tuna population and fisheries. *Climatic Change*, **119**(**1**), 95-109.

Lejeusne, C., P. Chevaldonné, C. Pergent-Martini, C.F. Boudouresque, and T. Pérez, 2010: Climate change effects on a miniature ocean: the highly diverse, highly impacted Mediterranean Sea. *Trends in Ecology & Evolution*, **25**(**4**), 250-260.

Levin, L.A., W. Ekau, A.J. Gooday, F. Jorissen, J.J. Middelburg, S.W.A. Naqvi, C. Neira, N.N. Rabalais, and J. Zhang, 2009: Effects of natural and human-induced hypoxia on coastal benthos. *Biogeosciences*, **6**(**10**), 2063-2098.

Levitus, S., J. Antonov, and T. Boyer, 2005: Warming of the world ocean, 1955-2003. *Geophysical Research Letters*, **32**(**2**), L02604, doi:10.1029/2004GL021592.

Levitus, S., J.I. Antonov, T.P. Boyer, R.A. Locarnini, H.E. Garcia, and A.V. Mishonov, 2009: Global ocean heat content 1955-2008 in light of recently revealed instrumentation problems. *Geophysical Research Letters*, **36**(**7**), L07608, doi:10.1029/2008GL037155.

Lewis, E.L. and N.P. Fofonoff, 1979: A practical salinity scale. *Journal of Physical Oceanography*, **9(2)**, 446.

Li, L., J. Xu, and R. Cai, 2002: Trends of sea level rise in the South China Sea during the 1990s: an altimetry result. *Chinese Science Bulletin*, **47**(**7**), 582-585.

Li, S., K.-F. Yu, T.-R. Chen, Q. Shi, and H.-L. Zhang, 2011: Assessment of coral bleaching using symbiotic zooxanthellae density and satellite remote sensing data in the Nansha Islands, South China Sea. *Chinese Science Bulletin*, **56**(**10**), 1031-1037.

Lin, C., X. Ning, J. Su, Y. Lin, and B. Xu, 2005: Environmental changes and the responses of the ecosystems of the Yellow Sea during 1976-2000. *Journal of Marine Systems*, **55**(**3**), 223-234.

Lin, G. and Q. Yang, 2011: Interdecadal variation of distribution features of phytoplankton in the Taiwan Strait to global climate change. *Chinese Journal of Applied & Environmental Biology*, **17**(**5**), 615-623.

Lindegren, M., C. Möllmann, A. Nielsen, K. Brander, B.R. MacKenzie, and N.C. Stenseth, 2010: Ecological forecasting under climate change: the case of Baltic cod. *Proceedings of the Royal Society B*, **277**(**1691**), 2121-2130.

Lindley, J.A. and R.R. Kirby, 2010: Climate-induced changes in the North Sea Decapoda over the last 60 years. *Climate Research*, **42**(**3**), 257-264.

Lindley, J.A., G. Beaugrand, C. Luczak, J.M. Dewarumez, and R.R. Kirby, 2010: Warm-water decapods and the trophic amplification of climate in the North Sea. *Biology Letters*, **6**(**6**), 773-776.

Ling, S.D., 2008: Range expansion of a habitat-modifying species leads to loss of taxonomic diversity: a new and impoverished reef state. *Oecologia*, **156**(**4**), 883-894.

Ling, S.D., C.R. Johnson, S. Frusher, and C.K. King, 2008: Reproductive potential of a marine ecosystem engineer at the edge of a newly expanded range. *Global Change Biology*, **14**(**4**), 907-915.

Ling, S.D., C.R. Johnson, S.D. Frusher, and K.R. Ridgway, 2009: Overfishing reduces resilience of kelp beds to climate-driven catastrophic phase shift. *Proceedings of the National Academy of Sciences of the United States of America*, **106**(**52**), 22341-22345.

Link, J.S., B. Bogstad, H. Sparholt, and G.R. Lilly, 2009a: Trophic role of Atlantic cod in the ecosystem. *Fish and Fisheries*, **10**(**1**), 58-87.

Link, J.S., W.T. Stockhausen, G. Skaret, W. Overholtz, B.A. Megrey, H. Gjosaeter, S. Gaichas, A. Dommasnes, J. Falk-Petersen, J. Kane, F.J. Mueter, K.D. Friedland, and J.A. Hare, 2009b: A comparison of biological trends from four marine ecosystems: synchronies, differences, and commonalities. *Progress in Oceanography*, **81**(**1-4**), 29-46.

Litzow, M.A. and L. Ciannelli, 2007: Oscillating trophic control induces community reorganization in a marine ecosystem. *Ecology Letters*, **10**(**12**), 1124-1134.

Litzow, M.A., J.D. Urban, and B.J. Laurel, 2008: Increased spatial variance accompanies reorganization of two continental shelf ecosystems. *Ecological Applications*, **18**(**6**), 1331-1337.

Liu, C., Y. Du, Q. Zhang, T. Chen, and D. Wang, 2007: Responses of oceans to global warming and observation evidence in the South China Sea. *Advances in Climate Change Research*, **3**(**1**), 8-13.

Livingston, P.A. and S. Tjelmeland, 2000: Fisheries in boreal ecosystems. *International Council for the Exploration of the Sea (ICES) Journal of Marine Science*, **57**(**3**), 619-627.

Llewellyn, L.E., 2010: Revisiting the association between sea surface temperature and the epidemiology of fish poisoning in the South Pacific: reassessing the link between ciguatera and climate change. *Toxicon*, **56**(**5**), 691-697.

Lo Iacono, C., M.A. Mateo, E. Gràcia, L. Guasch, R. Carbonell, L. Serrano, O. Serrano, and J. Dañobeitia, 2008: Very high-resolution seismo-acoustic imaging of seagrass meadows (Mediterranean Sea): implications for carbon sink estimates. *Geophysical Research Letters*, **35**, L18601, doi:10.1029/2008GL034773.

Longhurst, A., 1998. *Ecological Geography of the Sea*. Academic Press, San Diego, CA, USA and London, UK, 398 pp.

Lotze, H.K., M. Coll, A.M. Magera, C. Ward-Paige, and L. Airoldi, 2011: Recovery of marine animal populations and ecosystems. *Trends in Ecology & Evolution*, **26**(**11**), 595-605.

Lough, J.M., 2012: Small change, big difference: sea surface temperature distributions for tropical coral reef ecosystems, 1950-2011. *Journal of Geophysical Research: Oceans*, **117**(**C9**), C09018, doi:10.1029/2012JC008199.

Lough, J.M., G.A. Meehl, and M.J. Salinger, 2011: Observed in projected changes in surface climate of the tropical Pacific. In: *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change* [Bell, J.D., J.E. Johnson, and A.J. Hobday (eds.)]. Secretariat of the Pacific Community, Noumea, New Caledonia, pp. 49-99.

Lucey, S.M. and J.A. Nye, 2010: Shifting species assemblages in the Northeast US Continental Shelf Large Marine Ecosystem. *Marine Ecology Progress Series*, **415**, 23-33.

Luchetta, A., C. Cantoni, and G. Catalano, 2010: New observations of CO_2-induced acidification in the northern Adriatic Sea over the last quarter century. *Chemistry and Ecology*, **26(Suppl. 1)**, 1-17.

Ludwig, W., E. Dumont, M. Meybeck, and S. Heussner, 2009: River discharges of water and nutrients to the Mediterranean and Black Sea: major drivers for ecosystem changes during past and future decades? *Progress in Oceanography*, **80**(**3-4**), 199-217.

Luisetti, T., E.L. Jackson, and R.K. Turner, 2013: Valuing the European 'coastal blue carbon' storage benefit. *Marine Pollution Bulletin*, **71**(**1-2**), 101-106.

Lundsten, L., J.P. Barry, G.M. Cailliet, D.A. Clague, A.P. DeVogelaere, and J.B. Geller, 2009: Benthic invertebrate communities on three seamounts off southern and central California, USA. *Marine Ecology Progress Series*, **374**, 23-32.

Ma, Z., Z. Xu, and J. Zhou, 2009: Effect of global warming on the distribution of *Lucifer intermedius* and *L. hanseni* (Decapoda) in the Changjiang estuary. *Progress in Natural Science*, **19**(**10**), 1389-1395.

Mabus, R., 2010: *Department of the Navy's Energy Program for Security and Independence*. United States Department of the Navy, DIANE Publishing, Darby, PA, USA, 24 pp.

Mackas, D.L., R. Goldblatt, and A.G. Lewis, 1998: Interdecadal variation in developmental timing of *Neocalanus plumchrus* populations at Ocean Station P in the subarctic North Pacific. *Canadian Journal of Fisheries and Aquatic Sciences*, **55**(**8**), 1878-1893.

MacKenzie, B.R., and D. Schiedek, 2007a: Daily ocean monitoring since the 1860s shows record warming of northern European seas. *Global Change Biology*, **13**(**7**), 1335-1347.

MacKenzie, B.R., and D. Schiedek, 2007b: Long-term sea surface temperature baselines-time series, spatial covariation and implications for biological processes. *Journal of Marine Systems*, **68**(**3-4**), 405-420.

MacKenzie, B.R., H. Gislason, C. Möllmann, and F.W. Köster, 2007: Impact of 21st century climate change on the Baltic Sea fish community and fisheries. *Global Change Biology*, **13**(**7**), 1348-1367.

MacKenzie, B.R., H.E.M. Meier, M. Lindegren, S. Neuenfeldt, M. Eero, T. Blenckner, M.T. Tomczak, and S. Niiranen, 2012: Impact of climate change on fish population dynamics in the Baltic Sea: a dynamical downscaling investigation. *AMBIO: A Journal of the Human Environment*, **41(6)**, 626-636.

MacNeil, M.A., N.A. Graham, J.E. Cinner, N.K. Dulvy, P.A. Loring, S. Jennings, N.V. Polunin, A.T. Fisk, and T.R. McClanahan, 2010: Transitional states in marine fisheries: adapting to predicted global change. *Philosophical Transactions of the Royal Society B*, **365**(**1558**), 3753-3763.

Madsen, K.S. and N.K. Højerslev, 2009: Long-term temperature and salinity records from the Baltic Sea transition zone. *Boreal Environment Research*, **14**(**1**), 125-131.

Maier, C., J. Hegeman, M.G. Weinbauer, and J.-P. Gattuso, 2009: Calcification of the cold-water coral *Lophelia pertusa*, under ambient and reduced pH. *Biogeosciences*, **6**(**8**), 1671-1680.

Maier, C., A. Schubert, M.M.B. Sànchez, M.G. Weinbauer, P. Watremez, and J.-P. Gattuso, 2013: End of the century pCO_2 levels do not impact calcification in Mediterranean cold-water corals. *PLoS ONE*, **8**(**4**), e62655, doi:10.1371/journal.pone.0062655.

Makino, M., H. Matsuda, and Y. Sakurai, 2009: Expanding fisheries co-management to ecosystem-based management: a case in the Shiretoko World Natural Heritage area, Japan. *Marine Policy*, **33**(**2**), 207-214.

Manhique, A.J., C.J.C. Reason, L. Rydberg, and N. Fauchereau, 2011: ENSO and Indian Ocean sea surface temperatures and their relationships with tropical temperate troughs over Mozambique and the Southwest Indian Ocean. *International Journal of Climatology*, **31**(**1**), 1-13.

Mantua, N.J. and S.R. Hare, 2002: The Pacific Decadal Oscillation. *Journal of Oceanography*, **58**(**1**), 35-44.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis, 1997: A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society*, **78**(**6**), 1069-1079.

Manzello, D.P., 2010: Coral growth with thermal stress and ocean acidification: lessons from the eastern tropical Pacific. *Coral Reefs*, **29**(**3**), 749-758.

Manzello, D.P., J.A. Kleypas, D.A. Budd, C.M. Eakin, P.W. Glynn, and C. Langdon, 2008: Poorly cemented coral reefs of the eastern tropical Pacific: possible insights into reef development in a high-CO_2 world. *Proceedings of the National Academy of Sciences of the United States of America*, **105**(**30**), 10450-10455.

Marbà, N. and C.M. Duarte, 2010: Mediterranean warming triggers seagrass (*Posidonia oceanica*) shoot mortality. *Global Change Biology*, **16**(**8**), 2366-2375.

Martin, J.H. and S.E. Fitzwater, 1988: Iron deficiency limits phytoplankton growth in the north-east Pacific subarctic. *Nature*, **331(6154)**, 341-343.

Martin, S. and J.-P. Gattuso, 2009: Response of Mediterranean coralline algae to ocean acidification and elevated temperature. *Global Change Biology*, **15**(**8**), 2089-2100.

Marullo, S., V. Artale, and R. Santoleri, 2011: The SST multi-decadal variability in the Atlantic-Mediterranean region and its relation to AMO. *Journal of Climate*, **24**(**16**), 4385-4401.

Massuti, E., S. Monserrat, P. Oliver, J. Moranta, J.L. López-Jurado, M. Marcos, M. Hidalgo, B. Guijarro, A. Carbonell, and P. Pereda, 2008: The influence of oceanographic scenarios on the population dynamics of demersal resources in the western Mediterranean: hypothesis for hake and red shrimp off Balearic Islands. *Journal of Marine Systems*, **71**(**3-4**), 421-438.

Matsuno, T., J.S. Lee, and S. Yanao, 2009: The Kuroshio exchange with the South and East China Seas. *Ocean Science*, **5**(**3**), 303-312.

McAllister, C.D., T.R. Parsons, and J.D.H. Strickland, 1960: Primary productivity and fertility at Station "P" in the North-East Pacific Ocean. *International Council for the Exploration of the Sea (ICES) Journal of Marine Science*, **25**(**3**), 240-259.

McCarthy, J.J., C. Garside, J.L. Nevins, and R.T. Barber, 1996: New production along 140°W in the equatorial Pacific during and following the 1992 El Niño event. *Deep-Sea Research Part II: Topical Studies in Oceanography*, **43**(**4-6**), 1065-1093.

McClain, C.R., S.R. Signorini, and J.R. Christian, 2004: Subtropical gyre variability observed by ocean-color satellites. *Deep-Sea Research Part II: Topical Studies in Oceanography*, **51(1-3)**, 281-301.

McClanahan, T.R., M. Ateweberhan, N.A.J. Graham, S.K. Wilson, C.R. Sebastián, M.M.M. Guillaume, and J.H. Bruggemann, 2007: Western Indian Ocean coral communities: bleaching responses and susceptibility to extinction. *Marine Ecology Progress Series*, **337**, 1-13.

McClanahan, T.R., J.E. Cinner, J. Maina, N.A.J. Graham, T.M. Daw, S.M. Stead, A. Wamukota, K. Brown, M. Ateweberhan, V. Venus, and N.V.C. Polunin, 2008: Conservation action in a changing climate. *Conservation Letters*, **1**(**2**), 53-59.

McClanahan, T.R., M. Ateweberhan, J. Omukoto, and L. Pearson, 2009a: Recent seawater temperature histories, status, and predictions for Madagascar's coral reefs. *Marine Ecology Progress Series*, **380**, 117-128.

McClanahan, T.R., E. Weil, and J. Maina, 2009b: Strong relationship between coral bleaching and growth anomalies in massive *Porites*. *Global Change Biology*, **15**(**7**), 1804-1816.

McClanahan, T.R., E. Weil, J. Cortés, A.H. Baird, and M. Ateweberhan, 2009c: Consequences of coral bleaching for sessile reef organisms. In: *Coral Bleaching: Patterns, Processes, Causes and Consequences*, [van Oppen, M.J.H. and J.M. Lough (eds.)]. Springer-Verlag, Berlin, Germany, pp. 121-138.

McClatchie, S., R. Goericke, R. Cosgrove, G. Auad, and R. Vetter, 2010: Oxygen in the Southern California Bight: multidecadal trends and implications for demersal fisheries. *Geophysical Research Letters*, **37**(**19**), L19602, doi:10.1029/2010GL044497.

McGowan, J.A., D.R. Cayan, and L.M. Dorman, 1998: Climate-ocean variability and ecosystem response in the Northeast Pacific. *Science*, **281**(**5374**), 210-216.

McIlgorm, A., S. Hanna, G. Knapp, P. Le Floc'H, F. Millerd, and M. Pan, 2010: How will climate change alter fishery governance? Insights from seven international case studies. *Marine Policy*, **34**(**1**), 170-177.

McKinnell, S.M. and M.J. Dagg (eds.), 2010: *Marine Ecosystems of the North Pacific Ocean, 2003-2008*. PICES Special Publication No. 4, North Pacific Marine Science Organization (PICES), Sydney, BC, Canada, 393 pp.

McKinnell, S.M., S. Batten, S.J. Bograd, J.L. Boldt, N. Bond, S. Chiba, M.J. Dagg, M.G.G. Foreman, G.L. Hunt Jr., J.R. Irvine, O.N. Katugin, V. Lobanov, D.L. Mackas, P. Mundy, V. Radchenko, Y.J. Ro, H. Sugisaki, F.A. Whitney, A. Yatsu, and S. Yoo, 2010: Status and trends of the North Pacific Ocean, 2003-2008. In: *Marine Ecosystems of the North Pacific Ocean, 2003-2008* [McKinnell, S.M. and M.J. Dagg (eds.)]. PICES Special Publication No. 4, North Pacific Marine Science Organization (PICES), Sydney, BC, Canada, pp. 1-55.

McLeod, E., R. Moffitt, A. Timmermann, R. Salm, L. Menviel, M.J. Palmer, E.R. Selig, K.S. Casey, and J.F. Bruno, 2010: Warming seas in the Coral Triangle: coral reef vulnerability and management implications. *Coastal Management*, **38**(**5**), 518-539.

McLeod, E., G.L. Chmura, S. Bouillon, R. Salm, M. Björk, C.M. Duarte, C.E. Lovelock, W.H. Schlesinger, and B.R. Silliman, 2011: A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. *Frontiers in Ecology and the Environment*, **9**(**10**), 552-560.

McMichael, A.J., R.E. Woodruff, and S. Hales, 2006: Climate change and human health: present and future risks. *Lancet*, **367**(**9513**), 859-869.

McNeil, B.I. and R.J. Matear, 2008: Southern Ocean acidification: a tipping point at 450-ppm atmospheric CO_2. *Proceedings of the National Academy of Sciences of the United States of America*, **105**(**48**), 18860-18864.

McPhaden, M.J. and D. Zhang, 2002: Slowdown of the meridional overturning circulation in the upper Pacific Ocean. *Nature*, **415**(**6872**), 603-608.

MEA, 2005: *Ecosystems and Human Well-Being: Current State and Trends: Findings of the Condition and Trends Working Group, Vol. 1* [Hassan, R., R. Scholes, and N. Ash (eds.)]. Millennium Ecosystem Assessment (MEA), Island Press, Washington, DC, USA, 917 pp.

Meehl, G.A. and J.M. Arblaster, 2011: Decadal variability of Asian–Australian Monsoon–ENSO–TBO relationships. *Journal of Climate*, **24**(**18**), 4925-4940.

Meehl, G.A., A. Hu, and B.D. Santer, 2009: The mid-1970s climate shift in the Pacific and the relative roles of forced versus inherent decadal variability. *Journal of Climate*, **22**(**3**), 780-792.

Menard, F., F. Marsac, E. Bellier, and B. Cazelles, 2007: Climatic oscillations and tuna catch rates in the Indian Ocean: a wavelet approach to time series analysis. *Fisheries Oceanography*, **16**(**1**), 95-104.

Mendelssohn, R. and F. Schwing, 2002: Common and uncommon trends in SST and wind stress in the California and Peru–Chile current systems. *Progress in Oceanography*, **53**(**2**), 141-162.

Menge, B.A., F. Chan, K.J. Nielsen, E. di Lorenzo, and J. Lubchenco, 2009: Climatic variation alters supply-side ecology: impact of climate patterns on phytoplankton and mussel recruitment. *Ecological Monographs*, **79**(**3**), 379-395.

Merino, G., M. Barange, C. Mullon, and L. Rodwell, 2010: Impacts of global environmental change and aquaculture expansion on marine ecosystems. *Global Environmental Change: Human and Policy Dimensions*, **20**(**4**), 586-596.

Merino, G., M. Barange, J.L. Blanchard, J. Harle, R. Holmes, I. Allen, E.H. Allison, M.C. Badjeck, N.K. Dulvy, J. Holt, S. Jennings, C. Mullon, and L. Rodwell, 2012: Can marine fisheries and aquaculture meet fish demand from a growing human population in a changing climate? *Global Environmental Change*, **22(4)**, 795-806.

Mertz, O., K. Halsnæs, J.E. Olesen, and K. Rasmussen, 2009: Adaptation to climate change in developing countries. *Environmental Management*, **43**(**5**), 743-752.

Mestas-Nuñez, A.M. and A.J. Miller, 2006: Interdecadal variability and climate change in the eastern tropical Pacific: a review. *Progress in Oceanography*, **69**(**2-4**), 267-284.

Mieszkowska, N., S.J. Hawkins, M.T. Burrows, and M.A. Kendall, 2007: Long-term changes in the geographic distribution and population structures of *Osilinus lineatus* (Gastropoda: Trochidae) in Britain and Ireland. *Journal of the Marine Biological Association of the United Kingdom*, **87**(**2**), 537-545.

Miller, K.A., G.R. Munro, U.R. Sumaila, and W.W.L. Cheung, 2013: Governing marine fisheries in a changing climate: a game-theoretic perspective. *Canadian Journal of Agricultural Economics*, **61(2 SI)**, 309-334.

Mills, D.J., L. Westlund, G. Graaf, Y. de Kura, R. Willman, and K. Kelleher, 2011: Under-reported and undervalued: small-scale fisheries in the developing world*.* In: *Small-Scale Fisheries Management: Frameworks and Approaches for the Developing World* [Pomeroy, R.S. and N.L. Andrew (eds.)]. CABI (formerly CAB International), Wallingford, UK. pp. 1-15.

Minobe, S., 1997: A 50-70 year climatic oscillation over the North Pacific and North America. *Geophysical Research Letters*, **24**(**6**), 683-686.

Mohan, R., K. Verma, L.P. Mergulhao, D.K. Sinha, S. Shanvas, and M.V.S. Guptha, 2006: Seasonal variation of pteropods from the Western Arabian Sea sediment trap. *Geo-Marine Letters*, **26**(**5**), 265-273.

Molinero, J.C., F. Ibanez, S. Souissi, M. Chifflet, and P. Nival, 2005: Phenological changes in the Northwestern Mediterranean copepods *Centropages typicus* and *Temora stylifera* linked to climate forcing. *Oecologia*, **145**(**4**), 640-649.

Möllmann, C., G. Kornilovs, M. Fetter, F.W. Köster, and H.H. Hinrichsen, 2003: The marine copepod, *Pseudocalanus elongatus*, as a mediator between climate variability and fisheries in the Central Baltic Sea. *Fisheries Oceanography*, **12**(**4-5**), 360-368.

Möllmann, C., G. Kornilovs, M. Fetter, and F.W. Köster, 2005: Climate, zooplankton, and pelagic fish growth in the central Baltic Sea. *International Council for the Exploration of the Sea (ICES) Journal of Marine Science*, **62**(**7**), 1270-1280.

Möllmann, C., R. Diekman, B. Müller-Karulis, G. Kornilovs, M. Plikshs, and P. Axe, 2009: Reorganization of a large marine ecosystem due to atmospheric and anthropogenic pressure: a discontinuous regime shift in the Central Baltic Sea. *Global Change Biology*, **15(6)**, 1377-1393.

Monteiro, P.M.S., A.K. van der Plas, J.L. Mélice, and P. Florenchie, 2008: Interannual hypoxia variability in a coastal upwelling system: ocean-shelf exchange, climate and ecosystem-state implications. *Deep Sea Research Part I: Oceanographic Research Papers*, **55**(**4**), 435-450.

Morita, K., S.H. Morita, and M.A. Fukuwaka, 2006: Population dynamics of Japanese pink salmon (*Oncorhynchus gorbuscha*): are recent increases explained by hatchery programs or climatic variations? *Canadian Journal of Fisheries and Aquatic Sciences*, **63(1)**, 55-62.

Moron, V., 2003: Long-term variability of the Mediterranean Sea surface temperature (1856-2000). *Compte Rendus Geoscience*, **335**(**9**), 721-727.

Mountain, D.G. and J. Kane, 2010: Major changes in the Georges Bank ecosystem, 1980s to the 1990s. *Marine Ecology Progress Series*, **398**, 81-91.

Movilla, J., E. Calvo, C. Pelejero, R. Coma, E. Serrano, P. Fernández-Vallejo, and M. Ribes, 2012: Calcification reduction and recovery in native and non-native Mediterranean corals in response to ocean acidification. *Journal of Experimental Marine Biology and Ecology*, **438**, 144-153.

Moy, A.D., W.R. Howard, S.G. Bray, and T.W. Trull, 2009: Reduced calcification in modern Southern Ocean planktonic foraminifera. *Nature Geoscience*, **2**(**4**), 276-280.

Mueter, F.J. and M.A. Litzow, 2008: Sea ice retreat alters the biogeography of the Bering Sea continental shelf. *Ecological Applications*, **18**(**2**), 309-320.

Muhling, B.A., S.-K. Lee, J.T. Lamkin, and Y. Liu, 2011: Predicting the effects of climate change on bluefin tuna (*Thunnus thynnus*) spawning habitat in the Gulf of Mexico. *International Council for the Exploration of the Sea (ICES) Journal of Marine Science*, **68**(**6**), 1051-1062.

Mumby, P.J., J.R.M. Chisholm, A.J. Edwards, C.D. Clark, E.B. Roark, S. Andréfouët, and J. Jaubert, 2001: Unprecedented bleaching-induced mortality in *Porites* spp. at Rangiroa Atoll, French Polynesia. *Marine Biology*, **139**(**1**), 183-189.

Mumby, P.J., R. Vitolo, and D.B. Stephenson, 2011: Temporal clustering of tropical cyclones and its ecosystem impacts. *Proceedings of the National Academy of Sciences of the United States of America*, **108**(**43**), 17626-17630.

Munday, P.L., D.L. Dixson, J.M. Donelson, G.P. Jones, M.S. Pratchett, G.V. Devitsina, and K.B. Doving, 2009: Ocean acidification impairs olfactory discrimination and homing ability of a marine fish. *Proceedings of the National Academy of Sciences of the United States of America*, **106**(**6**), 1848-1852.

Murray, J.W., H.W. Jannasch, S. Honjo, R.F. Anderson, W.S. Reeburgh, Z. Top, G.E. Friederich, L.A. Codispoti, and E. Izdar, 1989: Unexpected changes in the oxic/anoxic interface in the Black Sea. *Nature*, **338**(**6214**), 411-413.

Myers, S.S. and J.A. Patz, 2009: Emerging threats to human health from global environmental change. *Annual Review of Environment and Resources*, **34**, 223-252.

Nakamura, N., H. Kayanne, H. Iijima, T.R. McClanahan, S.K. Behera, and T. Yamagata, 2011: Footprints of IOD and ENSO in the Kenyan coral record. *Geophysical Research Letters*, **38**(**24**), L24708, doi:10.1029/2011GL049877.

Nakanowatari, T., K.I. Ohshima, and M. Wakatsuchi, 2007: Warming and oxygen decrease of intermediate water in the northwestern North Pacific, originating from the Sea of Okhotsk, 1955-2004. *Geophysical Research Letters*, **34**(**4**), L04602, doi:10.1029/2006GL028243.

Narayan, N., A. Paul, S. Mulitza, and M. Schulz, 2010: Trends in coastal upwelling intensity during the late 20th century. *Ocean Science*, **6**(**3**), 815-823.

Naylor, R.L., R.W. Hardy, D.P. Bureau, A. Chiu, M. Elliott, A.P. Farrell, I. Forster, D.M. Gatlin, R.J. Goldburg, K. Hua, and P.D. Nichols, 2009: Feeding aquaculture in an era of finite resources. *Proceedings of the National Academy of Sciences of the United States of America*, **106(42)**, 15103-15110.

Nellemann, C., E. Corcoran, C.M. Duarte, L. Valdés, C. De Young, L. Fonseca, and G. Grimsditch (eds.), 2009: *Blue Carbon: The Role of Healthy Oceans in Binding Carbon – A Rapid Response Assessment*. Report produced as an Inter-agency collaboration between the United Nations Environment Programme (UNEP), the Food and Agricultural Organization of the United Nations (FAO) and the Intergovernmental Oceanographic Commission (IOC)/ United Nations Educational, Scientific and Cultural Organization (UNESCO), UNEP, Nairobi, Kenya and Global Resource Information Database (GRID)-Arendal, Arendal, Norway, 78 pp.

Nicol, S.J., V. Allain, G.M. Pilling, J. Polovina, M. Coll, J. Bell, P. Dalzell, P. Sharples, R. Olson, S. Griffiths, J.M. Dambacher, J. Young, A. Lewis, J. Hampton, J. Jurado Molina, S. Hoyle, K. Briand, N. Bax, P. Lehodey, and P. Williams, 2013: An ocean

30

observation system for monitoring the affects of climate change on the ecology and sustainability of pelagic fisheries in the Pacific Ocean. *Climatic Change*, **119(1)**, 131-145.

Ning, X., C. Lin, Q. Hao, C. Liu, F. Le, and J. Shi, 2009: Long term changes in the ecosystem in the northern South China Sea during 1976-2004. *Biogeosciences*, **6**(**10**), 2227-2243.

Ning, X., C. Lin, J. Su, C. Liu, Q. Hao, and F. Le, 2011: Long-term changes of dissolved oxygen, hypoxia, and the responses of the ecosystems in the East China Sea from 1975 to 1995. *Journal of Oceanography*, **67**(**1**), 59-75.

Norman-López, A., É. Plagányi, T. Skewes, E. Poloczanska, D. Dennis, M.T. Gibbs, and P. Bayliss, 2013: Linking physiological, population and socio-economic assessments of climate-change impacts on fisheries. *Fisheries Research,* **148**, 18-26.

Nøttestad, L., K.R. Utne, V. Anthonypillai, Ø. Tangen, J.W. Valdemarsen, G.J. Óskarsson, S. Sveinbjörnsoon, S. Jónsson, H. Debes, E. Mortensen, L. Smith, A. Ólafsdottir, and J.A. Jacobsen, 2013: *Cruise Report from the Coordinated Ecosystem Survey (IESSMS) with M/V "Libas", M/V "Eros", M/V "Finnur Frí i" and R/V "Arni Fridriksson" in the Norwegian Sea and Surrounding Waters, 2 July - 9 August 2013.* Working Document to ICES Working Group on Widely Distributed Stocks (WGWIDE), 27 August - 2 September 2013, International Council for the Exploration of the Sea (ICES) Headquarters, Copenhagen, Denmark, 42 pp.

Nye, J.A., J.S. Link, J.A. Hare, and W.J. Overholtz, 2009: Changing spatial distribution of fish stocks in relation to climate and population size on the Northeast United States continental shelf. *Marine Ecology Progress Series*, **393**, 111-129.

Obura, D. and S. Mangubhai, 2011: Coral mortality associated with thermal fluctuations in the Phoenix Islands, 2002-2005. *Coral Reefs*, **30(3)**, 607-619.

Oguz, T. and V. Velikova, 2010: Abrupt transition of the northwestern Black Sea shelf ecosystem from a eutrophic to an alternative pristine state. *Marine Ecology Progress Series*, **405**, 231-242.

Oguz, T., T. Cokacar, P. Malanotte-Rizzoli, and H.W. Ducklow, 2003: Climatic warming and accompanying changes in the ecological regime of the Black Sea during 1990s. *Global Biogeochemical Cycles*, **17**(**3**), 1088, doi:10.1029/2003GB002031.

Oguz, T., B. Fach, and B. Salihoglu, 2008: Invasion dynamics of the alien ctenophore *Mnemiopsis leidyi* and its impact on anchovy collapse in the Black Sea. *Journal of Plankton Research*, **30**(**12**), 1385-1397.

Ohmura, A., 2009: Observed decadal variations in surface solar radiation and their causes. *Journal of Geophysical Research: Atmospheres*, **114(D10)**, D00D05, doi:10.1029/2008JD011290.

Orr, J.C., V.J. Fabry, O. Aumont, L. Bopp, S.C. Doney, R.A. Feely, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joos, R.M. Key, K. Lindsay, E. Maier-Reimer, R. Matear, P. Monfray, A. Mouchet, R.G. Najjar, G.K. Plattner, K.B. Rodgers, C.L. Sabine, J.L. Sarmiento, R. Schlitzer, R.D. Slater, I.J. Totterdell, M.F. Weirig, Y. Yamanaka, and A. Yool, 2005: Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*, **437**(**7059**), 681-686.

Oude Elferink, A.G., 2012: Governance principles for areas beyond national jurisdiction. *The International Journal of Marine and Coastal Law*, **27(2)**, 205-259.

Overland, J., S. Rodionov, S. Minobe, and N. Bond, 2008: North Pacific regime shifts: definitions, issues and recent transitions. *Progress in Oceanography*, **77**(**2-3**), 92-102.

Overland, J.E., J. Alheit, A. Bakun, J.W. Hurrell, D.L. Mackas, and A.J. Miller, 2010: Climate controls on marine ecosystems and fish populations. *Journal of Marine Systems*, **79**(**3-4**), 305-315.

Parmesan, C., C. Duarte, E. Poloczanska, A.J. Richardson, and M.C. Singer, 2011: Commentary: overstretching attribution. *Nature Climate Change*, **1**(**1**), 2-4.

Parrish, R.H., F.B. Schwing, and R. Mendelssohn, 2000: Mid-latitude wind stress: the energy source for climatic shifts in the North Pacific Ocean. *Fisheries Oceanography*, **9**(**3**), 224-238.

Pascual, M., X. Rodó, S.P. Ellner, R. Colwell, and M.J. Bouma, 2000: Cholera dynamics and El Niño-Southern Oscillation. *Science*, **289**(**5485**), 1766-1769.

Patz, J.A., D. Campbell-Lendrum, T. Holloway, and J.A. Foley, 2005: Impact of regional climate change on human health. *Nature*, **438**(**7066**), 310-317.

Pauly, D. and V. Christensen, 1995: Primary production required to sustain global fisheries. *Nature*, **374(6519)**, 255-257.

Pecl, G., S. Frusher, C. Gardner, M. Haward, A. Hobday, S. Jennings, M. Nursey-Bray, A. Punt, H. Revill, and I. van Putten, 2009: *The East Coast Tasmanian Rock Lobster Fishery – Vulnerability to Climate Change Impacts and Adaptation Response Options.* Report to the Australian Government Department of Climate Change, Australia, Commonwealth of Australia, Canberra, ACT, Australia, 114 pp.

Peñaflor, E., W. Skirving, A. Strong, S. Heron, and L. David, 2009: Sea-surface temperature and thermal stress in the Coral Triangle over the past two decades. *Coral Reefs*, **28**(**4**), 841-850.

Pendleton, L., D.C. Donato, B.C. Murray, S. Crooks, W.A. Jenkins, S. Sifleet, C. Craft, J.W. Fourqurean, J.B. Kauffman, N. Marbà, P. Megonigal, E. Pidgeon, D. Herr, D. Gordon, and A. Baldera, 2012: Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems. *PLoS ONE*, **7**(**9**), e43542, doi:10.1371/journal.pone.004354.

Pennington, J.T., K.L. Mahoney, V.S. Kuwahara, D.D. Kolber, R. Calienes, and F.P. Chavez, 2006: Primary production in the eastern tropical Pacific: a review. *Progress in Oceanography*, **69**(**2-4**), 285-317.

Perry, A.L., P.J. Low, J.R. Ellis, and J.D. Reynolds, 2005: Climate change and distribution shifts in marine fishes. *Science*, **308**(**5730**), 1912-1915.

Perry, R.I., P. Cury, K. Brander, S. Jennings, C. Möllmann, and B. Planque, 2010: Sensitivity of marine systems to climate and fishing: concepts, issues and management responses. *Journal of Marine Systems*, **79**, 427-435.

Peterson, W.T. and F.B. Schwing, 2003: A new climate regime in northeast Pacific ecosystems. *Geophysical Research Letters*, **30**(**17**), 1896, doi:10.1029/2003GL017528.

Pickering, T., B. Ponia, C. Hair, P.C. Southgate, E. Poloczanska, L. Della Patrona, A. Teitelbaum, C.V. Mohan, M. Phillips, and J.D. Bell, 2011: Vulnerability of aquaculture in the tropical Pacific to climate change. In: *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change* [Bell, J.D., J.E. Johnson, and A.J. Hobday (eds.)]. Secretariat of the Pacific Community, Noumea, New Caledonia, pp. 647-732.

Pierce, D.W., P.J. Gleckler, T.P. Barnett, B.D. Santer, and P.J. Durack, 2012: The fingerprint of human-induced changes in the ocean's salinity and temperature fields. *Geophysical Research Letters*, **39**(**21**), L21704, doi:10.1029/2012GL053389.

Pinnegar, J., T. Watt, and K. Kennedy, 2012: *Climate Change Risk Assessment for the Marine and Fisheries Sector*. CCRA – UK 2012 Climate Change Risk Assessment, DEFRA Project Code GA0204, Department for Environment Food and Rural Affairs (DEFRA), London, UK, 204 pp.

Pinsky, M.L., B. Worm, M.J. Fogarty, J.L. Sarmiento, and S.A. Levin, 2013: Marine taxa track local climate velocities. *Science*, **341(6151)**, 1239-1242.

Pitcher, T.J., D. Kalikoski, K. Short, D. Varkey, and G. Pramod, 2009: An evaluation of progress in implementing ecosystem-based management of fisheries in 33 countries. *Marine Policy*, **33**(**2**), 223-232.

Pitt, N.R., E.S. Poloczanska, and A.J. Hobday, 2010: Climate-driven range changes in Tasmanian intertidal fauna. *Marine and Freshwater Research*, **61**(**9**), 963-970.

Plagányi, É.E., T. Skewes, M. Haddon, and N. Dowling, 2013: Risk management tools for sustainable fisheries management under changing climate: a sea cucumber example. *Climatic Change*, **119(1)**, 181-197.

Poloczanska, E.S., S.J. Hawkins, A.J. Southward, and M.T. Burrows, 2008: Modeling the response of populations of competing species to climate change. *Ecology*, **89**(**11**), 3138-3149.

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

Polovina, J.J. and P.A. Woodworth, 2012: Declines in phytoplankton cell size in the subtropical oceans estimated from satellite remotely-sensed temperature and chlorophyll, 1998-2007. *Deep Sea Research Part II: Topical Studies in Oceanography*, **77-80**(**SI**), 82-88.

Polovina, J.J., E.A. Howell, and M. Abecassis, 2008: Ocean's least productive waters are expanding. *Geophysical Research Letters*, **35**(**3**), L03618, doi:10.1029/2007GL031745.

Polovina, J.J., J.P. Dunne, P.A. Woodworth, and E.A. Howell, 2011: Projected expansion of the subtropical biome and contraction of the temperate and equatorial upwelling biomes in the North Pacific under global warming. *International Council for the Exploration of the Sea (ICES) Journal of Marine Science*, **68**(**6**), 986-995.

Pomeroy, R.S. and N.L. Andrew, 2011: *Small-Scale Fisheries Management: Frameworks and Approaches for the Developing World*. CABI (formerly CAB International), Wallingford, UK and Cambridge, MA, USA, 247 pp.

Pörtner, H.-O., 2002: Climate variations and the physiological basis of temperature dependent biogeography: systemic to molecular hierarchy of thermal tolerance in animals. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology*, **132**(**4**), 739-761.

Pörtner, H.-O., 2010: Oxygen- and capacity-limitation of thermal tolerance: a matrix for integrating climate-related stressor effects in marine ecosystems. *Journal of Experimental Biology*, **213**(**6**), 881-893.

Pörtner, H.-O., B. Berdal, R. Blust, O. Brix, A. Colosimo, B. De Wachter, A. Giuliani, T. Johansen, T. Fischer, R. Knust, G. Lannig, G. Naevdal, A. Nedenes, G. Nyhammer, F.J. Sartoris, I. Serendero, P. Sirabella, S. Thorkildsen, and M. Zakhartsev, 2001: Climate induced temperature effects on growth performance, fecundity and recruitment in marine fish: developing a hypothesis for cause and effect relationships in Atlantic cod (*Gadus morhua*) and common eelpout (*Zoarces viviparus*). *Continental Shelf Research*, **21**(**18-19**), 1975-1997.

Pörtner, H.-O., C. Bock, K. Deigweiher, and M. Lucassen, 2007: Environmental change and the role of acid-base regulation in marine ectotherms. (Paper presented at the Seventh International Congress of Comparative Physiology and Biochemistry, Salvador, Bahia, Brazil, August 12-16, 2007). *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology*, **148**(**Suppl. 1**), S142, www.sciencedirect.com/science/article/pii/S1095643307014195.

Power, S.B. and I.N. Smith, 2007: Weakening of the Walker Circulation and apparent dominance of El Niño both reach record levels, but has ENSO really changed? *Geophysical Research Letters*, **34**(**18**), L18702, doi:10.1029/2007GL030854.

Power, S., T. Casey, C. Folland, A. Colman, and V. Mehta, 1999: Inter-decadal modulation of the impact of ENSO on Australia. *Climate Dynamics*, **15(5)**, 319-324.

Prakash, S. and R. Ramesh, 2007: Is the Arabian Sea getting more productive? *Current Science*, **92**(**5**), 667-670.

Pratchett, M.S., P.L. Munday, S.K. Wilson, N.A.J. Graham, J.E. Cinner, D.R. Bellwood, G.P. Jones, N.V.C. Polunin, and T.R. McClanahan, 2008: Effects of climate-induced coral bleaching on coral-reef fishes – ecological and economic consequences. *Oceanography and Marine Biology: An Annual Review*, **46**, 251-296.

Pratchett, M.S., A.S. Hoey, S.K. Wilson, V. Messmer, and N.A.J. Graham, 2011a: Changes in biodiversity and functioning of reef fish assemblages following coral bleaching and coral loss. *Diversity*, **3**(**3**), 424-452.

Pratchett, M.S., P.L. Munday, N.A.J. Graham, M. Kronen, S. Pinca, K. Friedman, T.D. Brewer, J.D. Bell, S.K. Wilson, J.E. Cinner, J.P. Kinch, R.J. Lawton, A.J. Williams, L. Chapman, F. Magron, and A. Webb, 2011b: Vulnerability of coastal fisheries in the tropical Pacific to climate change. In: *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change* [Bell, J.D., J.E. Johnson, and A.J. Hobday (eds.)]. Secretariat of the Pacific Community, Noumea, New Caledonia. pp. 167-185.

Przeslawski, R., I. Falkner, M.B. Ashcroft, and P. Hutchings, 2012: Using rigorous selection criteria to investigate marine range shifts. *Estuarine, Coastal and Shelf Science*, **113**, 205-212.

Qi, Q., R. Cai, and Q. Zhang, 2010: Low-frequency variability of the heat transport in source area of Kuroshio and its relation to SST in China seas. *Journal of Oceanography in Taiwan Strait*, **29**(**1**), 106-113 (in Chinese).

Qiu, Y., Z. Lin, and Y. Wang, 2010: Responses of fish production to fishing and climate variability in the northern South China Sea. *Progress in Oceanography*, **85**(**3-4**), 197-212.

Rabalais, N.N., R.E. Turner, R.J. Díaz, and D. Justić, 2009: Global change and eutrophication of coastal waters. *International Council for the Exploration of the Sea (ICES) Journal of Marine Science*, **66**(**7**), 1528-1537.

Rabalais, N.N., R.J. Diaz, L.A. Levin, R.E. Turner, D. Gilbert, and J. Zhang, 2010: Dynamics and distribution of natural and human-caused hypoxia. *Biogeosciences*, **7**(**2**), 585-619.

Racault, M.F., C. Le Quéré, E. Buitenhuis, S. Sathyendranath, and T. Platt, 2012: Phytoplankton phenology in the global ocean. *Ecological Indicators*, **14**(**1**), 152-163.

Rahman, C., 2012: The implications of climate change for maritime security forces. In: *Climate Change and the Oceans: Gauging the Legal and Policy Currents in the Asia Pacific and Beyond* [Warner, R. and C. Schofield (eds.)]. Edward Elgar Publishing, Cheltenham, UK and Northampton, MA, USA, pp. 167-199.

Raitsos, D.E., G. Beaugrand, D. Georgopoulos, A. Zenetos, A.M. Pancucci-Papadopoulou, A. Theocharis, and E. Papathanassiou, 2010: Global climate change amplifies the entry of tropical species into the Eastern Mediterranean Sea. *Limnology and Oceanography*, **55**(**4**), 1478-1484.

Raitsos, D.E., I. Hoteit, P.K. Prihartato, T. Chronis, G. Triantafyllou, and Y. Abualnaja, 2011: Abrupt warming of the Red Sea. *Geophysical Research Letters*, **38**, L14601, doi:10.1029/2011GL047984.

Randolph, M.F., C. Gaudin, S.M. Gourvenec, D.J. White, N. Boylan, and M.J. Cassidy, 2010: Recent advances in offshore geotechnics for deep water oil and gas developments. *Ocean Engineering*, **38(7)**, 818-834.

Raven, J., K. Caldeira, H. Elderfield, O. Hoegh-Guldberg, P. Liss, U. Riebesell, J. Shepherd, C. Turley, and A. Watson, 2005: *Ocean Acidification due to Increasing Atmospheric Carbon Dioxide*. Policy document 12/05, The Royal Society, London, UK, 60 pp.

Rayfuse, R. and R. Warner, 2012: Climate change mitigation activities in the ocean: turning up the regulatory heat. In: *Climate Change and the Oceans: Gauging the Legal and Policy Currents in the Asia Pacific and Beyond* [Warner, R. and C. Schofield (eds.)]. Edward Elgar Publishing, Cheltenham, UK and Northampton, MA, USA, pp. 234-262.

Rayner, N.A., D.E. Parker, E.B. Horton, C.K. Folland, L.V. Alexander, D.P. Rowell, E.C. Kent, and A. Kaplan, 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research: Atmospheres*, **108**(**D14**), 4407, doi:10.1029/2002JD002670.

Reid, P.C., N.P. Holliday, and T.J. Smyth, 2001: Pulses in the eastern margin current and warmer water off the north west European shelf linked to North Sea ecosystem changes. *Marine Ecology Progress Series*, **215**, 283-287.

Reid, P.C., D.G. Johns, M. Edwards, M. Starr, M. Poulin, and P. Snoeijs, 2007: A biological consequence of reducing Arctic ice cover: arrival of the Pacific diatom *Neodenticula seminae* in the North Atlantic for the first time in 800,000 years. *Global Change Biology*, **13**(**9**), 1910-1921.

Richter, I., S.K. Behera, Y. Masumoto, B. Taguchi, N. Komori, and T. Yamagata, 2010: On the triggering of Benguela Niños: remote equatorial versus local influences. *Geophysical Research Letters*, **37**(**20**), L20604, doi:10.1029/2010GL044461.

Ridgwell, A. and D.N. Schmidt, 2010: Past constraints on the vulnerability of marine calcifiers to massive carbon dioxide release. *Nature Geoscience*, **3**(**3**), 196-200.

Riegl, B., 2002: Effects of the 1996 and 1998 positive sea-surface temperature anomalies on corals, coral diseases and fish in the Arabian Gulf (Dubai, UAE). *Marine Biology*, **140**(**1**), 29-40.

Riegl, B., 2003: Climate change and coral reefs: different effects in two high-latitude areas (Arabian Gulf, South Africa). *Coral Reefs*, **22**(**4**), 433-446.

Riegl, B. and W.E. Piller, 2003: Possible refugia for reefs in times of environmental stress. *International Journal of Earth Sciences*, **92**(**4**), 520-531.

Riegl, B.M., S.J. Purkis, A.S. Al-Cibahy, M.A. Abdel-Moati, and O. Hoegh-Guldberg, 2011: Present limits to heat-adaptability in corals and population-level responses to climate extremes. *PLoS ONE*, **6**(**9**), e24802, doi:10.1371/journal.pone.0024802.

Riegl, B.M., A.W. Bruckner, G.P. Rowlands, S.J. Purkis, and P. Renaud, 2012: Red Sea coral reef trajectories over 2 decades suggest increasing community homogenization and decline in coral size. *PLoS ONE*, **7**(**5**), e38396, doi:10.1371/journal.pone.0038396.

Rixen, M., J.-M. Beckers, S. Levitus, J. Antonov, T. Boyer, C. Maillard, M. Fichaut, E. Balopoulos, S. Iona, H. Dooley, M.-J. Garcia, B. Manca, A. Giorgetti, G. Manzella, N. Mikhailov, N. Pinardi, and M. Zavatarelli, 2005: The Western Mediterranean Deep Water: a proxy for climate change. *Geophysical Research Letters*, **32**(**12**), L12608, doi:10.1029/2005GL022702.

Robinson, J., P. Guillotreau, R. Jiménez-Toribio, F. Lantz, L. Nadzon, J. Dorizo, C. Gerry, and F. Marsac, 2010: Impacts of climate variability on the tuna economy of Seychelles. *Climate Research*, **43**(**3**), 149-162.

Rockström, J., W. Steffen, K. Noone, A. Persson, F.S. Chapin III, E.F. Lambin, T.M. Lenton, M. Scheffer, C. Folke, H.J. Schellnhuber, B. Nykvist, C.A. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sorlin, P.K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R.W. Corell, V.J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and J.A. Foley, 2009: A safe operating space for humanity. *Nature*, **461**(**7263**), 472-475.

Rodó, X., M. Pascual, G. Fuchs, and A.S. Faruque, 2002: ENSO and cholera: a nonstationary link related to climate change? *Proceedings of the National Academy of Sciences of the United States of America*, **99**(**20**), 12901-12906.

Rodolfo-Metalpa, R., C. Lombardi, S. Cocito, J.M. Hall-Spencer, and M.C. Gambi, 2010: Effects of ocean acidification and high temperatures on the bryozoan *Myriapora truncata* at natural CO_2 vents. *Marine Ecology*, **31**(**3**), 447-456.

Rodolfo-Metalpa, R., F. Houlbrèque, É. Tambutté, F. Boisson, C. Baggini, F.P. Patti, R. Jeffree, M. Fine, A. Foggo, J.-P. Gattuso, and J.M. Hall-Spencer, 2011: Coral and mollusc resistance to ocean acidification adversely affected by warming. *Nature Climate Change*, **1**(**6**), 308-312.

Rogelj, J., M. Meinshausen, and R. Knutti, 2012: Global warming under old and new scenarios using IPCC climate sensitivity range estimates. *Nature Climate Change*, **2**, 248-253.

Rouault, M., B. Pohl, and P. Penven, 2010: Coastal oceanic climate change and variability from 1982 to 2009 around South Africa. *African Journal of Marine Science*, **32**(**2**), 237-246.

Roy, C., C.D. van der Lingen, J.C. Coetzee, and J.R.E. Lutjeharms, 2007: Abrupt environmental shift associated with changes in the distribution of Cape anchovy *Engraulis encrasicolus* spawners in the southern Benguela. *African Journal of Marine Science*, **29**(**3**), 309-319.

Ruckelshaus, M., S. Doney, H. Galindo, J. Barry, F. Chan, J. Duffy, C. English, S. Gaines, J. Grebmeier, and A. Hollowed, 2013: Securing ocean benefits for society in the face of climate change. *Marine Policy*, **40**, 154-159.

Rykaczewski, R.R. and J.P. Dunne, 2010: Enhanced nutrient supply to the California Current Ecosystem with global warming and increased stratification in an earth system model. *Geophysical Research Letters*, **37(21)**, L21606, doi:10.1029/2010GL045019.

Sabatés, A., P. Martin, J. Lloret, and V. Raya, 2006: Sea warming and fish distribution: the case of the small pelagic fish, *Sardinella aurita*, in the western Mediterranean. *Global Change Biology*, **12**(**11**), 2209-2219.

Sabine, C.L., R.A. Feely, N. Gruber, R.M. Key, K. Lee, J.L. Bullister, R. Wanninkhof, C.S. Wong, D.W. Wallace, B. Tilbrook, F.J. Millero, T.H. Peng, A. Kozyr, T. Ono, and A.F. Rios, 2004: The oceanic sink for anthropogenic CO_2. *Science*, **305**(**5682**), 367-371.

Sakamoto, T.T., H. Hasumi, M. Ishii, S. Emori, T. Suzuki, T. Nishimura, and A. Sumi, 2005: Responses of the Kuroshio and the Kuroshio Extension to global warming in a high-resolution climate model. *Geophysical Research Letters*, **32**(**14**), L14617, doi:10.1029/2005GL023384.

Samuelsson, M., 1996: Interannual salinity variations in the Baltic Sea during the period 1954-1990. *Continental Shelf Research*, **16**(**11**), 1463-1477.

Santana-Casiano, J.M., M. González-Dávila, and I.R. Ucha, 2009: Carbon dioxide fluxes in the Benguela upwelling system during winter and spring: a comparison between 2005 and 2006. *Deep-Sea Research Part II: Topical Studies in Oceanography*, **56**(**8-10**), 533-541.

Sarmiento, J.L., R. Slater, R. Barber, L. Bopp, S.C. Doney, A.C. Hirst, J. Kleypas, R. Matear, U. Mikolajewicz, P. Monfray, V. Soldatov, S.A. Spall, and R. Stouffer, 2004: Response of ocean ecosystems to climate warming. *Global Biogeochemical Cycles*, **18**(**3**), GB3003, doi:10.1029/2003GB002134.

Schluter, M.H., A. Merico, M. Reginatto, M. Boersma, K.H. Wiltshire, and W. Greve, 2010: Phenological shifts of three interacting zooplankton groups in relation to climate change. *Global Change Biology*, **16**(**11**), 3144-3153.

Schofield, C. and A. Arsana, 2012: Climate change and the limits of maritime jurisdiction. In: *Climate Change and the Oceans: Gauging the Legal and Policy Currents in the Asia Pacific and Beyond* [Warner, R. and C. Schofield (eds.)]. Edward Elgar Publishing, Cheltenham, UK and Northampton, MA, USA, pp. 127-152.

Schofield, O., S.M. Glenn, M.A. Moline, M. Oliver, A. Irwin, Y. Chao, and M. Arrott, 2013: Ocean observatories and information: building a global ocean observing network. In: *Earth System Monitoring*, [Orcutt, J. (ed.)]. Springer, New York, NY, USA, pp. 319-336.

Schøyen, H. and S. Bråthen, 2011: The Northern Sea Route versus the Suez Canal: cases from bulk shipping. *Journal of Transport Geography*, **19(4)**, 977-983.

Scott, D., C.M. Hall, and S. Gössling, 2012a: *Tourism and Climate Change: Impacts, Adaptation and Mitigation*. Taylor and Francis, Abingdon, UK and New York, NY, USA, 464 pp.

Scott, D., M.C. Simpson, and R. Sim, 2012b: The vulnerability of Caribbean coastal tourism to scenarios of climate change related sea level rise. *Journal of Sustainable Tourism*, **20**(**6**), 883-898.

Seibel, B.A. and P.J. Walsh, 2001: Potential impacts of CO_2 injection on deep-sea biota. *Science*, **294**(**5541**), 319-320.

Serrano, E., R. Coma, M. Ribes, B. Weitzmann, M. García, and E. Ballesteros, 2013: Rapid northward spread of a zooxanthellate coral enhanced by artificial structures and sea warming in the western Mediterranean. *PLoS ONE*, **8**(**1**), e52739, doi:10.1371/journal.pone.0052739.

Shaffer, G., S.M. Olsen, and J.O.P. Pedersen, 2009: Long-term ocean oxygen depletion in response to carbon dioxide emissions from fossil fuels. *Nature Geoscience*, **2**(**2**), 105-109.

Sherman, K., I.M. Belkin, K.D. Friedland, J. O'Reilly, and K. Hyde, 2009: Accelerated warming and emergent trends in fisheries biomass yields of the world's large marine ecosystems. *AMBIO: A Journal of the Human Environment*, **38**(**4**), 215-224.

Shoji, J., S. Toshito, K. Mizuno, Y. Kamimura, M. Hori, and K. Hirakawa, 2011: Possible effects of global warming on fish recruitment: shifts in spawning season and latitudinal distribution can alter growth of fish early life stages through changes in daylength. *International Council for the Exploration of the Sea (ICES) Journal of Marine Science*, **68**(**6**), 1165-1169.

Signorini, S.R. and C.R. McClain, 2012: Subtropical gyre variability as seen from satellites. *Remote Sensing Letters*, **3**(**6**), 471-479.

Signorini, S.R., R.G. Murtugudde, C.R. McClain, J.R. Christian, J. Picaut, and A.J. Busalacchi, 1999: Biological and physical signatures in the tropical and subtropical Atlantic. *Journal of Geophysical Research: Oceans*, **104**(**C8**), 18367-18382.

Silverman, J., B. Lazar, and J. Erez, 2007: Effect of aragonite saturation, temperature, and nutrients on the community calcification rate of a coral reef. *Journal of Geophysical Research: Oceans*, **112(C5)**, C05004, doi:10.1029/2006JC003770.

Silverman, J., B. Lazar, L. Cao, K. Caldeira, and J. Erez, 2009: Coral reefs may start dissolving when atmospheric CO_2 doubles. *Geophysical Research Letters*, **36(5)**, L05606, doi:10.1029/2008GL036282.

Simpson, S.D., S. Jennings, M.P. Johnson, J.L. Blanchard, P.J. Schon, D.W. Sims, and M.J. Genner, 2011: Continental shelf-wide response of a fish assemblage to rapid warming of the sea. *Current Biology*, **21**(**18**), 1565-1570.

Smith, C.R., F.C. De Leo, A.F. Bernardino, A.K. Sweetman, and P.M. Arbizu, 2008: Abyssal food limitation, ecosystem structure and climate change. *Trends in Ecology & Evolution*, **23**(**9**), 518-528.

Smith Jr., K.L. and R.S. Kaufmann, 1999: Long-term discrepancy between food supply and demand in the deep eastern North Pacific. *Science*, **284**(**5417**), 1174-1177.

Smith Jr., K.L., H.A. Ruhl, B.J. Bett, D.S.M. Billett, R.S. Lampitt, and R.S. Kaufmann, 2009: Climate, carbon cycling, and deep-ocean ecosystems. *Proceedings of the National Academy of Sciences of the United States of America*, **106**(**46**), 19211-19218.

Smith, T.B., M.E. Brandt, J.M. Calnan, R.S. Nemeth, J. Blondeau, E. Kadison, M. Taylor, and P. Rothenberger, 2013: Convergent mortality responses of Caribbean coral species to seawater warming. *Ecosphere*, **4**(**7**), 87, doi:10.1890/ES13-00107.1.

Southward, A., 1980: The western English Channel – an inconstant ecosystem? *Nature*, **285(5764)**, 361-366.

Southward, A.J., S.J. Hawkins, and M.T. Burrows, 1995: Seventy years' observations of changes in distribution and abundance of zooplankton and intertidal organisms in the western English Channel in relation to rising sea temperature. *Journal of Thermal Biology*, **20**(**1-2**), 127-155.

Southward, A.J., O. Langmead, N.J. Hardman-Mountford, J. Aiken, G.T. Boalch, P.R. Dando, M.J. Genner, I. Joint, M.A. Kendall, N.C. Halliday, R.P. Harris, R. Leaper, N. Mieszkowska, R.D. Pingree, A.J. Richardson, D.W. Sims, T. Smith, A.W. Walne, and S.J. Hawkins, 2005: Long-term oceanographic and ecological research in the western English Channel. In: *Advances in Marine Biology, Vol. 47* [Southward, A.J., P.A. Tyler, C.M. Young, and L.A. Fuiman (eds.)]. Elsevier Academic Press, San Diego, CA, USA and London, UK, pp. 1-105.

Stenevik, E.K. and S. Sundby, 2007: Impacts of climate change on commercial fish stocks in Norwegian waters. *Marine Policy*, **31**(**1**), 19-31.

Stott, P.A., N.P. Gillett, G.C. Hegerl, D.J. Karoly, D.A. Stone, X.B. Zhang, and F. Zwiers, 2010: Detection and attribution of climate change: a regional perspective. *Wiley Interdisciplinary Reviews: Climate Change*, **1**(**2**), 192-211.

Stramma, L., G.C. Johnson, J. Sprintall, and V. Mohrholz, 2008: Expanding oxygen-minimum zones in the tropical oceans. *Science*, **320**(**5876**), 655-658.

Stramma, L., S. Schmidtko, L.A. Levin, and G.C. Johnson, 2010: Ocean oxygen minima expansions and their biological impacts. *Deep-Sea Research Part I: Oceanographic Research Papers*, **57**(**4**), 587-595.

Stramma, L., E.D. Prince, S. Schmidtko, J. Luo, J.P. Hoolihan, M. Visbeck, D.W.R. Wallace, P. Brandt, and A. Körtzinger, 2012: Expansion of oxygen minimum zones may reduce available habitat for tropical pelagic fishes. *Nature Climate Change*, **2**(**1**), 33-37.

Strong, A.E., C.S. Barrientos, C. Duda, and J. Sapper, 1997: Improved satellite technique for monitoring coral reef bleaching. In: *Proceedings of the 8th International Coral Reef Symposium 1997, Vol. 2* [Lessios, H.A. and I.G. Macintyre (eds.)]. Smithsonian Tropical Research Institute, Panama City, Panama, pp. 1495-1498.

Strong, A.E., G. Liu, W. Skirving, and C.M. Eakin, 2011: NOAA's Coral Reef Watch program from satellite observations. *Annals of GIS*, **17**(**2**), 83-92.

Sugisaki, H., M. Nonaka, S. Ishizaki, K. Hidaka, T. Kameda, Y. Hirota, Y. Oozeki, H. Kubota, and A. Takasuka, 2010: Status and trends of the Kuroshio region, 2003-2008. In: *Marine Ecosystems of the North Pacific Ocean, 2003-2008*

[McKinnell, S.M. and M.J. Dagg (eds.)]. PICES Special Publication No. 4, North Pacific Marine Science Organization (PICES), Sydney, BC, Canada, pp. 330-359.

Sultan, N., P. Cochonat, J.P. Foucher, and J. Mienert, 2004: Effect of gas hydrates melting on seafloor slope instability. *Marine Geology*, **213**(**1-4**), 379-401.

Sumaila, U.R., W.W.L. Cheung, V.W.Y. Lam, D. Pauly, and S. Herrick, 2011: Climate change impacts on the biophysics and economics of world fisheries. *Nature Climate Change*, **1**(**9**), 449-456.

Sundby, S., 2000: Recruitment of Atlantic cod stocks in relation to temperature and advection of copepod populations. *Sarsia*, **85**(**4**), 277-298.

Sundby, S. and O. Nakken, 2008: Spatial shifts in spawning habitats of Arcto-Norwegian cod related to multidecadal climate oscillations and climate change. *International Council for the Exploration of the Sea (ICES) Journal of Marine Science*, **65**(**6**), 953-962.

Sweatman, H., S. Delean, and C. Syms, 2011: Assessing loss of coral cover on Australia's Great Barrier Reef over two decades, with implications for longer-term trends. *Coral Reefs*, **30(2)**, 521-531.

Tallis, H., A. Guerry, and G.C. Daily, 2013: Ecosystem services. In: *Encyclopedia of Biodiversity, 2nd edn., Vol. 3* [Levin, S.A. (ed.)]. Academic Press, Waltham, UK, pp. 96-104.

Tam, J., M.H. Taylor, V. Blaskovic, P. Espinoza, R.M. Ballón, E. Diaz, C. Wosnitza-Mendo, J. Arguelles, S. Purca, P. Ayón, L. Quipuzcoa, D. Gutiérrez, E. Goya, N. Ochoa, and M. Wolff, 2008: Trophic modeling of the Northern Humboldt Current Ecosystem, Part I: comparing trophic linkages under La Niña and El Niño conditions. *Progress in Oceanography*, **79**(**2-4**), 352-365.

Tang, Q., 2009: Changing states of the Yellow Sea Large Marine Ecosystem: anthropogenic forcing and climate impacts. In: *Sustaining the World's Large Marine Ecosystems* [Sherman, K., M.C. Aquarone, and S. Adams (eds.)]. International Union for Conservation of Nature and Natural Resources (IUCN), Gland, Switzerland, pp. 77-88.

Tang, Q., X. Jin, J. Wang, Z. Zhuang, Y. Cui, and T. Meng, 2003: Decadal-scale variations of ecosystem productivity and control mechanisms in the Bohai Sea. *Fisheries Oceanography*, **12**(**4-5**), 223-233.

Tang, X., F. Wang, Y. Chen, and M. Li, 2009: Warming trend in northern East China Sea in recent four decades. *Chinese Journal of Oceanology and Limnology*, **27**(**2**), 185-191.

Tåning, Å.V., 1949: On changes in the marine fauna of the North-Western Atlantic Area, with special reference to Greenland. *Rapports et Procès-Verbaux des Réunions du Conseil Permanent International pour l'Exploration de la Mer (CIEM) [International Council for the Exploration of the Sea (ICES)]*, **125**, 26-29.

Tåning, Å.V., 1953: Long term changes in hydrography and fluctuations in fish stocks. In: *International Commision for the Northwest Atlantic Fisheries: Annual Proceedings, Vol. 3, for the year 1952–53, Part 5 No. III*. Issued from the Headquarters of the Commission, Imperial Press, Ltd., Halifax, NS, Canada, pp. 69-77, icnaf.nafo.int/ap/ann-proc-v03.pdf.

Tanzil, J.T.I., B.E. Brown, A.W. Tudhope, and R.P. Dunne, 2009: Decline in skeletal growth of the coral *Porites lutea* from the Andaman Sea, South Thailand between 1984 and 2005. *Coral Reefs*, **28**(**2**), 519-528.

Tasker, M.L. (ed.), 2008: *The Effect of Climate Change on the Distribution and Abundance of Marine Species in the OSPAR Maritime Area*. ICES Cooperative Research Report No. 293, International Council for the Exploration of the Sea (ICES), Copenhagen, Denmark, 45 pp.

Taylor, G.T., F.E. Muller-Karger, R.C. Thunell, M.I. Scranton, Y. Astor, R. Varela, L.T. Ghinaglia, L. Lorenzoni, K.A. Fanning, and S. Hameed, 2012: Ecosystem responses in the southern Caribbean Sea to global climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **109**(**47**), 19315-19320.

Taylor, M.H., J. Tam, V. Blaskovic, P. Espinoza, R.M. Ballón, C. Wosnitza-Mendo, J. Arguelles, E. Diaz, S. Purca, N. Ochoa, P. Ayón, E. Goya, D. Gutiérrez, L. Quipuzcoa, and M. Wolff, 2008: Trophic modeling of the Northern Humboldt Current Ecosystem, Part II: elucidating ecosystem dynamics from 1995 to 2004 with a focus on the impact of ENSO. *Progress in Oceanography*, **79**(**2-4**), 366-378.

ter Hofstede, R., J.G. Hiddink, and A.D. Rijnsdorp, 2010: Regional warming changes fish species richness in the eastern North Atlantic Ocean. *Marine Ecology Progress Series*, **414**, 1-9.

Terray, L., M.E. Demory, M. Déqué, G. de Coetlogon, and E. Maisonnave, 2004: Simulation of late-twenty-first-century changes in wintertime atmospheric circulation over Europe due to anthropogenic causes. *Journal of Climate*, **17**(**24**), 4630-4635.

Terray, L., L. Corre, S. Cravatte, T. Delcroix, G. Reverdin, and A. Ribes, 2012: Near-surface salinity as nature's rain gauge to detect human influence on the tropical water cycle. *Journal of Climate*, **25**(**3**), 958-977.

Thackeray, S.J., T.H. Sparks, M. Frederiksen, S. Burthe, P.J. Bacon, J.R. Bell, M.S. Botham, T.M. Brereton, P.W. Bright, and L. Carvalho, 2010: Trophic level asynchrony in rates of phenological change for marine, freshwater and terrestrial environments. *Global Change Biology*, **16**(**12**), 3304-3313.

The MerMex Group, 2011: Marine ecosystems' responses to climatic and anthropogenic forcings in the Mediterranean. *Progress in Oceanography*, **91**(**2**), 97-166.

Thornes, J., M. Rennie, H. Marsden, and L. Chapman, 2012: *Climate Change Risk Assessment for the Transport Sector*. CCRA – UK 2012 Climate Change Risk Assessment, DEFRA Project Code GA0204, Department for the Environment, Food and Rural Affairs (DEFRA), London, UK, 140 pp.

Thresher, R.E., B.D. Tilbrook, S. Fallon, N.C. Wilson, and J. Adkins, 2011: Effects of chronic low carbonate saturation levels on the distribution, growth and skeletal chemistry of deep-sea corals and other seamount megabenthos. *Marine Ecology Progress Series*, **442**, 87-99.

Tian, Y.J., H. Kidokoro, T. Watanabe, Y. Igeta, H. Sakaji, and S. Ino, 2012: Response of yellowtail, *Seriola quinqueradiata*, a key large predatory fish in the Japan Sea, to sea water temperature over the last century and potential effects of global warming. *Journal of Marine Systems*, **91**(**1**), 1-10.

Tokinaga, H. and S.-P. Xie, 2011: Weakening of the equatorial Atlantic cold tongue over the past six decades. *Nature Geoscience*, **4**(**4**), 222-226.

Toresen, R. and O.J. Østvedt, 2000: Variation in abundance of Norwegian spring-spawning herring (*Clupea harengus*, Clupeidae) throughout the 20th century and the influence of climatic fluctuations. *Fish and Fisheries*, **1**(**3**), 231-256.

Touratier, F. and C. Goyet, 2011: Impact of the Eastern Mediterranean Transient on the distribution of anthropogenic CO_2 and first estimate of acidification for the Mediterranean Sea. *Deep-Sea Research Part I: Oceanographic Research Papers*, **58**(**1**), 1-15.

Trenberth, K.E., 1990: Recent observed interdecadal climate changes in the Northern Hemisphere. *Bulletin of the American Meteorological Society*, **71**(**7**), 988-993.

Trenberth, K.E. and D.J. Shea, 2006: Atlantic hurricanes and natural variability in 2005. *Geophysical Research Letters*, **33**(**12**), L12704, doi:10.1029/2006GL026894.

Tsamenyi, M. and Q. Hanich, 2012: Fisheries jurisdiction under the Law of the Sea Convention: rights and obligations in maritime zones under the sovereignty of Coastal States. *The International Journal of Marine and Coastal Law*, **27**(**4**), 783-793.

Tsikliras, A., 2008: Climate-related geographic shift and sudden population increase of a small pelagic fish (*Sardinella aurita*) in the eastern Mediterranean Sea. *Marine Biology Research*, **4**(**6**), 477-481.

Turley, C. and K. Boot, 2011: The ocean acidification challenges facing science and society. In: *Ocean Acidification* [Gattuso, J.-P. and L. Hansson (eds.)]. Oxford University Press, Oxford, UK, pp. 249-271.

Turner, R.E. and N.N. Rabalais, 1994: Coastal eutrophication near the Mississippi river delta. *Nature*, **368**(**6472**), 619-621.

Turner, R.E., N.N. Rabalais, and D. Justic, 2008: Gulf of Mexico hypoxia: alternate states and a legacy. *Environmental Science & Technology*, **42**(**7**), 2323-2327.

Turton, S., T. Dickson, W. Hadwen, B. Jorgensen, T. Pham, D. Simmons, P. Tremblay, and R. Wilson, 2010: Developing an approach for tourism climate change assessment: evidence from four contrasting Australian case studies. *Journal of Sustainable Tourism*, **18**(**3**), 429-447.

Tyler, W.B., K.T. Briggs, D.B. Lewis, and R.G. Ford, 1993: Seabird distribution and abundance in relation to oceanographic processes in the California Current System. In: *The Status, Ecology and Conservation of Marine Birds of the North Pacific* [Vermeer, K., K.T. Briggs, K.H. Morgan, and D. Siegel-Causey (eds.)]. Special Publication, Canadian Wildlife Series, Canadian Wildlife Service, Environment Canada, Ottawa, ON, Canada, pp. 48-60.

Ukrainskii, V. and Y.I. Popov, 2009: Climatic and hydrophysical conditions of the development of hypoxia in waters of the northwest shelf of the Black Sea. *Physical Oceanography*, **19**(**3**), 140-150.

UNCTAD, 2009a: *Review of Maritime Transport 2009.* Report by the United Nations Conference on Trade and Development (UNCTAD) Secretariat, United Nations, New York, NY, USA and Geneva, Switzerland, 221 pp.

UNCTAD, 2009b: *Multi-Year Expert Meeting on Transport and Trade Facilitation: Maritime Transport and the Climate Change Challenge, 16-18 February 2009, Geneva*. *Summary of Proceedings.* United Nations Conference on Trade and Development (UNCTAD), United Nations, Geneva, Switzerland, 52 pp.

UNWTO and UNEP, 2008: *Climate Change and Tourism: Responding to Global Challenges*. World Tourism Organization (UNWTO), Madrid, Spain and the United Nations Environment Programme (UNEP), Paris, France, 256 pp.

Van Dover, C.L., 2012: Hydrothermal vent ecosystems and conservation. *Oceanography*, **25**(**1**), 313-316.

van Hooidonk, R., J.A. Maynard, and S. Planes, 2013: Temporary refugia for coral reefs in a warming world. *Nature Climate Change*, **3**, 508-511.

van Vuuren, D.P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G.C. Hurtt, T. Kram, V. Krey, J.F. Lamarque, T. Masui, M. Meinshausen, N. Nakicenovik, S.J. Smith, and S.K. Rose, 2011: The representative concentration pathways: an overview. *Climatic Change*, **109(1-2)**, 5-31.

Vantrepotte, V. and F. Mélin, 2011: Inter-annual variations in the SeaWiFS global chlorophyll *a* concentration (1997-2007). *Deep-Sea Research Part I: Oceanographic Research Papers*, **58**(**4**), 429-441.

Vargas-Ángel, B., E.E. Looney, O.J. Vetter, and E.F. Coccagna, 2011: Severe, widespread El Niño-associated coral bleaching in the US Phoenix Islands. *Bulletin of Marine Science*, **87**(**3**), 623-638.

Vargas-Yáñez, M., F. Moya, M.C. Garcia-Martinez, E. Tel, P. Zunino, F. Plaza, J. Salat, J. Pascual, J.L. López-Jurado, and M. Serra, 2010: Climate change in the Western Mediterranean Sea 1900-2008. *Journal of Marine Systems*, **82**(**3**), 171-176.

Vecchi, G.A., B.J. Soden, A.T. Wittenerg, I.M. Held, A. Leetmaa, and M.J. Harrison, 2006: Weakening of tropical Pacific atmospheric circulation due to anthropogenic forcing. *Nature*, **441**(**7089**), 73-76.

Veitch, J., 2007: *The Changing State of the Benguela Current Large Marine Ecosystem: Expert Workshop on Climate Change and Variability and Impacts Thereof in the BCLME Region, 15-16 May 2007*. Workshop Report, Global Environment Facility (GEF), United Nations Development Program (UNDP), Washington, DC, USA, 55 pp.

Veron, J.E.N., L.M. Devantier, E. Turak, A.L. Green, S. Kininmonth, M. Stafford-Smith, and N. Peterson, 2009: Delineating the coral triangle. *Galaxea, Journal of Coral Reef Studies*, **11**(**2**), 91-100.

Wang, C. and S. Dong, 2010: Is the basin-wide warming in the North Atlantic Ocean related to atmospheric carbon dioxide and global warming? *Geophysical Research Letters*, **37**(**8**), L08707, doi:10.1029/2010GL042743.

Wang, M., J.E. Overland, D.B. Percival, and H.O. Mofjeld, 2006: Change in the arctic influence on Bering Sea climate during the twentieth century. *International Journal of Climatology*, **26**(**4**), 531-539.

Wang, M., N.A. Bond, and J.E. Overland, 2007a: Comparison of atmospheric forcing in four sub-arctic seas. *Deep-Sea Research Part II: Topical Studies in Oceanography*, **54**(**23-26**), 2543-2559.

Wang, M., J.E. Overland, V. Kattsov, J.E. Walsh, X. Zhang, and T. Pavlova, 2007b: Intrinsic versus forced variation in coupled climate model simulations over the Arctic during the twentieth century. *Journal of Climate*, **20**(**6**), 1093-1107.

Wang, X., J.R. Christian, R. Murtugudde, and A.J. Busalacchi, 2006: Spatial and temporal variability in new production in the equatorial Pacific during 1980-2003: physical and biogeochemical controls. *Deep-Sea Research Part II: Topical Studies in Oceanography*, **53**(**5-7**), 677-697.

Warner, R., 2012: Oceans beyond boundaries: environmental assessment frameworks. *International Journal of Marine and Coastal Law*, **27**(**2**), 481-499.

Warner, R. and C. Schofield (eds.), 2012: *Climate Change and the Oceans: Gauging the Legal and Policy Currents in the Asia Pacific and Beyond*. Edward Elgar Publishing, Cheltenham, UK and Northampton, MA, USA, 296 pp.

Waycott, M., C. Collier, K. McMahon, P. Ralph, L. McKenzie, J. Udy, and A. Grech, 2007: Vulnerability of seagrasses in the Great Barrier Reef to climate change. In: *Climate Change and the Great Barrier Reef: A Vulnerability Assessment* [Johnson, J.E. and P.A. Marshall (eds.)]. Great Barrier Reef Marine Park Authority (GBRMPA), Townsville, QLD, Australia and Department of the Environment and Heritage, Australian Greenhouse Office, Canberra, ACT, Australia, pp. 193-236.

Waycott, M., L.J. McKenzie, J.E. Mellors, J.E. Ellison, M.T. Sheaves, C. Collier, A.-M. Schwarz, A. Webb, J.E. Johnson, and C.E. Payri, 2011: Vulnerability of mangroves, seagrasses and intertidal flats in the tropical Pacific to climate change. In: *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change* [Bell, J.D., J.E. Johnson, and A.J. Hobday (eds.)]. Secretariat of the Pacific Community, Noumea, New Caledonia, pp. 297-368.

Weeks, S.J., B. Currie, and A. Bakun, 2002: Satellite imaging: massive emissions of toxic gas in the Atlantic. *Nature*, **415**(**6871**), 493-494.

West, J.M., S.H. Julius, P. Kareiva, C. Enquist, J.J. Lawler, B. Petersen, A.E. Johnson, and M.R. Shaw, 2009: US natural resources and climate change: concepts and approaches for management adaptation. *Environmental Management*, **44**(**6**), 1001-1021.

Westmacott, S., H. Cesar, and L. Pet-Soede, 2000: Socio-economic assessment of the impacts of the 1998 coral reef bleaching in the Indian Ocean: a summary. In: *Coral Reef Degradation in the Indian Ocean: Status Report 2000* [Souter, D., D. Obura, and O. Lindén (eds.)]. Coral Reef Degradation in the Indian Ocean Programme (CORDIO), SAREC Marine Science Program, Department of Zoology, Stockholm University, Stockholm, Sweden, pp. 143-159.

Wethey, D.S. and S.A. Woodin, 2008: Ecological hindcasting of biogeographic responses to climate change in the European intertidal zone. *Hydrobiologia*, **606(1)**, 139-151.

Whitney, F.A., H.J. Freeland, and M. Robert, 2007: Persistently declining oxygen levels in the interior waters of the eastern subarctic Pacific. *Progress in Oceanography*, **75**(**2**), 179-199.

Wild, M., 2009: Global dimming and brightening: a review. *Journal of Geophysical Research: Atmospheres*, **114**(**D10**), D00D16, doi:10.1029/2008JD011470.

Wilderbuer, T.K., A.B. Hollowed, W.J. Ingraham, P.D. Spencer, M.E. Conners, N.A. Bond, and G.E. Walters, 2002: Flatfish recruitment response to decadal climatic variability and ocean conditions in the eastern Bering Sea. *Progress in Oceanography*, **55**(**1-2**), 235-247.

Wilkinson, C., 2004. *Status of Coral Reefs of the World: 2004*. Australian Institute of Marine Science, Townsville, QLD, Australia, 264 pp.

Wilkinson, C. and G. Hodgson, 1999: Coral reefs and the 1997-1998 mass bleaching and mortality. *Nature & Resources*, **35**(**2**), 16-25.

Wiltshire, K.H. and B.F.J. Manly, 2004: The warming trend at Helgoland Roads, North Sea: phytoplankton response. *Helgoland Marine Research*, **58**(**4**), 269-273.

Wiltshire, K.H., A.M. Malzahn, K. Wirtz, W. Greve, S. Janisch, P. Mangelsdorf, B.F.J. Manly, and M. Boersma, 2008: Resilience of North Sea phytoplankton spring bloom dynamics: an analysis of long-term data at Helgoland Roads. *Limnology and Oceanography*, **53**(**4**), 1294-1302.

Wong, A.P.S., N.L. Bindoff, and J.A. Church, 2001: Freshwater and heat changes in the North and South Pacific Oceans between the 1960s and 1985-94. *Journal of Climate*, **14**(**7**), 1613-1633.

Wong, G.T.F., S.Y. Chao, Y.H. Li, and F.K. Shiah, 2000: The Kuroshio edge exchange processes (KEEP) study – an introduction to hypotheses and highlights. *Continental Shelf Research*, **20**(**4-5**), 335-347.

Wood, K.R. and J.E. Overland, 2010: Early 20th century Arctic warming in retrospect. *International Journal of Climatology*, **30**(**9**), 1269-1279.

Woodworth-Jefcoats, P.A., J.J. Polovina, J.P. Dunne, and J.L. Blanchard, 2013: Ecosystem size structure response to 21st century climate projection: large fish abundance decreases in the central North Pacific and increases in the California Current. *Global Change Biology*, **19**(**3**), 724-733.

World Bank and FAO, 2008: *The Sunken Billions: The Economic Justification for Fisheries Reform*. Architecture and Rural Development Series, The International Bank for Reconstruction and Development / The World Bank and the Food and Agriculture Organization of the United Nations (FAO), World Bank Publications, Washington, DC, USA, 100 pp.

Worm, B., R. Hilborn, J.K. Baum, T.A. Branch, J.S. Collie, C. Costello, M.J. Fogarty, E.A. Fulton, J.A. Hutchings, S. Jennings, O.P. Jensen, H.K. Lotze, P.M. Mace, T.R. McClanahan, C. Minto, S.R. Palumbi, A.M. Parma, D. Ricard, A.A. Rosenberg, R. Watson, and D. Zeller, 2009: Rebuilding global fisheries. *Science*, **325**(**5940**), 578-585.

WTTC, 2012: *The Economic Impact of Travel & Tourism 2012.* World Travel & Tourism Council (WTTC), London, UK, 20 pp.

Wu, L., W. Cai, L. Zhang, H. Nakamura, A. Timmermann, T. Joyce, M.J. McPhaden, M. Alexander, B. Qiu, M. Visbecks, P. Chang, and B. Giese, 2012: Enhanced warming over the global subtropical western boundary currents. *Nature Climate Change*, **2**(**3**), 161-166.

Wunsch, C. and P. Heimbach, 2008: How long to oceanic tracer and proxy equilibrium? *Quaternary Science Reviews*, **27**(**7-8**), 637-651.

Yatsu, A., K.Y. Aydin, J.R. King, G.A. McFarlane, S. Chiba, K. Tadokoro, M. Kaeriyama, and Y. Watanabe, 2008: Elucidating dynamic responses of North Pacific fish populations to climatic forcing: influence of life-history strategy. *Progress in Oceanography*, **77**(**2-3**), 252-268.

Yatsu, A., S. Chiba, Y. Yamanaka, S. Ito, Y. Shimizu, M. Kaeriyama, and Y. Watanabe, 2013: Climate forcing and the Kuroshio/Oyashio ecosystem. *International Council for the Exploration of the Sea (ICES) Journal of Marine Science*, **70**(**5**), 922-933.

Ye, S. and X. Huang, 2003: HABs in East China Sea: surveillance and monitoring. *Marine Environmental Science/Haiyang Huanjing Kexue*, **22**(**2**), 10-14.

Yoder, J.A., C.R. Mcclain, G.C. Feldman, and W.E. Esaias, 1993: Annual cycles of phytoplankton chlorophyll concentrations in the global ocean – a satellite view. *Global Biogeochemical Cycles*, **7**(**1**), 181-193.

Yu, J.Y. and H.Y. Kao, 2007: Decadal changes of ENSO persistence barrier in SST and ocean heat content indices: 1958-2001. *Journal of Geophysical Research: Atmospheres*, **112(D13)**, D13106, doi:10.1029/2006JD007654.

Yu, K.-F., J.-X. Zhao, Q. Shi, T.-G. Chen, P.-X. Wang, K.D. Collerson, and T.-S. Liu, 2006: U-series dating of dead *Porites* corals in the South China Sea: evidence for episodic coral mortality over the past two centuries. *Quaternary Geochronology*, **1**(**2**), 129-141.

Yunev, O.A., J. Carstensen, S. Moncheva, A. Khaliulin, G. Ærtebjerg, and S. Nixon, 2007: Nutrient and phytoplankton trends on the western Black Sea shelf in response to cultural eutrophication and climate changes. *Estuarine Coastal and Shelf Science*, **74**(**1-2**), 63-76.

Zeebe, R.E. and A. Ridgwell, 2011: Past changes in ocean carbonate chemistry. In: *Ocean Acidification* [Gattuso, J.-P. and L. Hansson (eds.)]. Oxford University Press, Oxford, UK, pp. 21-66.

Zeeberg, J., A. Corten, P. Tjoe-Awie, J. Coca, and B. Hamady, 2008: Climate modulates the effects of *Sardinella aurita* fisheries off Northwest Africa. *Fisheries Research*, **89**(**1**), 65-75.

Zervas, C.E., 2009. *Sea Level Variations of the United States, 1854-2006*. Technical Report NOS CO-OPS 053, National Oceanic and Atmospheric Administration (NOAA), Silver Spring, MD, USA, 194 pp.

Zhang, Q., Y. Hou, and T. Yan, 2011: Inter-annual and inter-decadal variability of Kuroshio heat transport in the East China Sea. *International Journal of Climatology*, **32(4)**, 481-488.

Zhang, X., J.A. Church, S.M. Platten, and D. Monselesan, 2014: Projection of subtropical gyre circulation and associated sea level changes in the Pacific based on CMIP3 climate models. *Climate Dynamics*, **43**, 131-144, doi:10.1007/s00382-013-1902-x.

Zhang, X., S. Shang, C. Zhang, Z. Lu, S. Shang, and X. Li, 2005: Potential influence of sea surface temperature on the interannual fluctuation of the catch and the distribution of chub mackerel and round scad in the Minnan-Taiwan Bank Fishing Ground, China. *Chinese Marine Science Bulletin*, **24**(**4**), 91-96.

Zhao, M., K. Yu, Q. Zhang, Q. Shi, and G.J. Price, 2012: Long-term decline of a fringing coral reef in the Northern South China Sea. *Journal of Coastal Research*, **28(5)**, 1088-1099.