Chapter 30. Open Oceans

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Executive Summary

The open ocean is undergoing fundamental change in response to the rise of greenhouse gases in Earth's atmosphere. Here, we analyze recent changes in the open ocean and explore their relationship to anthropogenic climate change. We separate the ocean into eight major regions [Figure 30-1, Table 30-1]: High Latitude Spring Bloom Systems, Eastern Boundary Currents, Western Boundary Systems, Equatorial Upwelling, Subtropical Gyres, Semi-Enclosed

Seas, the Deep Sea (>1,000 m), and Polar Seas. Polar Seas are not considered here as they are dealt with in Chapter 28. Many regions within the world's ocean have warmed significantly over the last 60 years [HadISST 1.1, 30.3.1.1, Table 30-2; Figure 30-3A], influenced by both climate change and other long-term cycles (e.g., ENSO, PDO, AMO), the influence of which is heightened at regional scales. The upper layers of the world's semi-enclosed seas show significant warming since 1982: Baltic (1.35°C), Black (0.96°C), Red (0.74°C) and Mediterranean Seas (0.71°C) [30.3.1.1, Figure30-3A]. Warming examined over 60 years is lower [Table 30-2]. Further warming is likely to expose semi-enclosed seas to greater thermal stratification, which will lead to reduced oxygen levels at depth and the spread of hypoxic zones, especially in the Baltic, Mediterranean, and Black Seas [30.5.6, *high confidence*]. Globally, isotherms are migrating rapidly (10-20 km yr^{-1}) across the ocean surface, especially at lower latitudes, setting the speed at which marine organisms must either move or adapt evolutionarily. Changes are also occurring in the timing of seasonal temperatures in both winter and summer [*high confidence*], which are crucial regulators of life-history events within a broad range of organisms [30.3.1.1, Figure 30-3 B-D]. Thermal stress events capable of having major ecological impacts, such as mass coral bleaching and mortality, have increased over the last 30 years [*high confidence*] [30.3.1.1, Figure 30-4] with heat stress are likely to reach unsustainable levels for coral ecosystems within the next few decades.

Many other aspects of ocean regions have changed over the past 60 years. Surface winds have changed significantly, with broad-scale consequences for coastal and oceanic conditions, particularly the height of waves, intensity of upwelling and shoaling of water column mixing. Some of the most profound decreases in water column mixing have occurred within the Pacific subtropical gyres with major increases also occurring at high latitudes in the southern hemisphere [*high confidence*; WGI Figure 2.38, WGI Figure 3.8; 30.3.1.4, Figure 30-5A]. Solar radiation has also varied since 1951 due to changes in aerosol optical depth and cloud coverage over the ocean, with the largest decreases occurring over the central Pacific and in temperate and polar regions [*medium confidence*, 30.3.1.1, Figure 30-5B-C]. Evidence that coastal upwelling will increase with climate change is equivocal with evidence of upwelling intensification in some regions but not all [30.5.1, 30.5.2, 30.5.4, 30.8.1]. Cooling, consistent with anthropogenic climate change, has occurred in some regions (e.g., High Spring Bloom Systems, Eastern Boundary Currents, Equatorial Upwelling [30.5.1, 30.5.2, 30.5.4, 30.8.1, Table 30-2]) as a result of intensified upwelling, glacier melt-water and other phenomena. Surface salinity has also changed regionally, with greatest increases being seen in the North and South Atlantic, off West Africa, Eastern Caribbean, and within the subtropical gyres of the three ocean basins. By contrast, the East, North and West Pacific Oceans along with parts of the Gulf of Mexico are showing strong freshening trends in surface waters. Increases in atmospheric CO_2 have reduced ocean pH and carbonate ion concentrations, with greatest changes at high latitudes. It is virtually certain that pH and carbonate ion saturation states will decrease below those seen in the last several million years with even modest increases in atmospheric CO_2 [30.3.2.2, 30.8.2, Figure 30-6; WGI Chapter 3; *high confidence*]. There is also increasing evidence that global climate change is affecting oxygen levels in the ocean, although this influence differences between locations and the influence of non-climate change factors. In the world's upwelling zones, oxygen levels are likely to decline in situations where upwelling is intensified and productivity increased [*medium confidence*].

Changes to the physical and chemical conditions within the ocean are driving profound changes in marine organisms and ecosystems across the ocean [*high confidence*]. In response, marine organisms are moving to higher latitudes in directions that are consistent with those expected under global climate change [30.4, Figures 30-8 to -10]. Over 80% of published studies that have investigated climate change trends in marine organisms over decades show responses that are consistent with those expected under anthropogenic climate change [*high confidence*, 30.4, Figures 30-8 to -10]. There is substantial evidence that the movement of populations towards higher latitudes has been highest among mobile organisms such as fish, crustaceans and zooplankton assemblages, and that the rate of movement has been highest among polar and temperate organisms and ecosystems [*medium confidence*]. Increased sea temperatures have also significantly altered the phenology or timing of key reproductive/life-cycle behaviour by 2-6 $day.decade^{-1}$ [30.4, Figures 30-8 to -10].

There is robust evidence that North Eastern Atlantic High Latitude Spring Bloom ecosystems are responding in ways that are consistent with climate change. Fish communities are being strongly impacted by climate change in the rapidly warming North Sea. Substantial biological impacts have been associated with warming since the late 1970s, including large-scale modification of the phenology, abundance and distribution of plankton assemblages and reorganisation of fish assemblages. However, substantial natural variability is embedded in the recent 30 years temperature increase in the entire Northeast Atlantic as part of the Atlantic Multidecadal Oscillation (AMO). These impacts have implications, potentially both positive and negative, for the future of the important fisheries within the High Latitude Spring Bloom Systems [30.5.1]. Many Western Boundary Systems are heavily impacted by a wide range of non-climate change related human activities making clear attribution of observed changes to climate change difficult. However, it is virtually certain that increasing sea temperatures within the Western Boundary Systems (0.56-0.81°C since 1950, excluding the Indian Ocean component which does not show consistent warming) have increased the frequency and severity of mass bleaching and mortality of coral reef ecosystems [e.g. Caribbean (0.47°C) and Coral Triangle (0.37°C, since 1980); 30.5.3.1.3, 30.5.3.1.6, 30.8.2].

Equatorial upwelling systems are strongly influenced by multi-year and decadal climate cycles such as the El Niño Southern Oscillation and Pacific Decadal Oscillation. These sources of variability tend to partially swamp trends due to climate change making attribution of recent changes difficult [30.5.3.1.4]. The core areas of the North Pacific, Indian Ocean and the North Atlantic subtropical gyres, characterised by highly oligotrophic waters, have expanded significantly since 1998. This change coincides with an increase in temperature and stratification of the water column [*high confidence*, 30.5.5, Figure 30-12]. Changes in Indian and Pacific Ocean temperature represent a major challenge for coral reef ecosystems. Based on the thermal tolerance of coral communities within these regions, future changes in sea temperature are likely to largely eliminate these important ecosystems [*high confidence*, 30.5.5.1, 30.8.2]. These changes have serious implications for the ecological goods and services. The distribution and abundance of key fisheries species such as tuna are highly sensitive to changes in sea temperature and are likely to change as sea temperatures increase [30.5.5.2].

Ensemble averages from AOGCM project sea temperatures increasing in most ocean regions although differences will be minimal under different Representative Concentration Pathways (RCP) by 2035. However, sea surface temperatures are likely to be 1-3°C higher under RCP8.5 than RCP2.6 by 2100 across most ocean regions [Table 30-4]. Based on the substantial response of open ocean systems to the relatively small amounts of warming so far, changes of this magnitude are likely to have major impacts on the structure and function of ocean ecosystems, and consequently the goods and services they provide for human communities. The rapid warming of the world's semi-enclosed seas will lead to greater thermal stratification, reduced mixing and consequently resulting in lower concentrations of oxygen at depth [*high confidence*]. The rapid increases in sea temperature in the Baltic, Black, Mediterranean, and Red seas, and the Arabian/Persian Gulf, will increase the frequency and severity of extreme conditions such as heat stress events, which have already caused major impacts on benthic invertebrate communities in most semi-enclosed seas [*high confidence*, 30.5.6.1]. Our understanding of the deep sea (> 1,000 m) remains limited despite the fact that it is the most extensive habitat on Earth. An increased supply of nutrients to the upper ocean parts of the ocean (through intensified upwelling) threatens deep sea ecosystems by increasing the rate of metabolism (and hence oxygen use; *high confidence*]. Similarly, a decrease in primary productivity such as seen in the subtropical gyres may reduce the availability of organic carbon to deep sea ecosystems [*low* to *medium confidence*, 30.5.7]. Changes to the supply of organic carbon to some parts of the deep sea will occur more rapidly than will changes in temperature which strongly suggests that deep-sea ecosystems will experience stress [*medium confidence*, 30.5.7].

Overall, there is substantial and compelling evidence that climate change has already influenced the world's oceans to the point where impacts have been detected in the physical, chemical and biological characteristics of the ocean. Projections of future change suggest that these impacts will increase, with serious implications for the ability of the ocean to provide goods and services at both local and global scales. Of growing concern is evidence of a reduced ability of the ocean to provide regulatory services that are essential to maintaining conditions on Earth. These changes, if they continue, pose serious risks for human communities.

30.1. Introduction

The world's oceans dominate Earth, interacting with its atmosphere, cryosphere, land and biosphere to determine planetary conditions. Oceans also directly influence human welfare through the provision of food, resources, economic and social security, and indirectly through the regulation of atmospheric gas content and distribution of heat across the planet. The present chapter evaluates the current impacts and future implications for open ocean regions of increased concentrations of atmospheric greenhouse gases and associated climate change. In doing so, this chapter assesses recent scientific evidence and examines the extent to which significant changes can be accurately detected and attributed to climate change. The impacts, risks and vulnerabilities associated with climate change are assessed within seven ocean regions, and the impacts and adaptation options for key ocean-based sectors discussed. Polar oceans are not directly considered here as they are given detailed treatment elsewhere (WGII Ch28, Polar Regions). It is also important to note that while the impact of climate change on open ocean regions directly influences the coastal and low-lying regions of multiple nations, a detailed discussion of these potential impacts also occurs elsewhere (e.g. WGII Ch5, Ch29).

30.1.1. Major Regions within the World's Oceans

There are considerable challenges in assessing the regional impacts of climate change in the world's oceans. Not only do oceans occupy 71% of the earth's surface, but they also contain a vast diversity of life forms and habitats, many of which are poorly documented and not easily studied. Devising an appropriate structure in order to explore the influence of climate change on the entire ocean system is consequently challenging, especially within the space allocated here. *Longhurst* [1998] identified over 75 distinct ecological provinces in the ocean, defined by physical forcing, and the structure and function of phytoplankton communities. This structure, however, yields far more regions than could be sensibly discussed in a single chapter. Consequently, we have used similar principles but have divided the non-polar ocean into seven larger regions that are similar to regions identified by *Barber* [1988]. In this case, our regions are unified by specific physical forcing and ecosystem structure that might be expected to respond to climate change in broadly distinct ways (Figure 30-1, Table 30-1). We also include the deep sea (>1000m) as a separate region which overlaps geographically with the six other ocean regions.

[INSERT FIGURE 30-1 HERE
Figure 30-1: The world's non-polar oceans have been separated into seven major regions, with polar oceans being excluded due to treatment elsewhere (Ch28). The chlorophyll concentration averaged over the period from Sep 1997 – 30 Nov 2010 (NASA) is also shown. Together with key oceanographic features, primary production was the basis for separating the ocean into the regions shown. The map insert shows the distribution of Deep Sea habitat (>1000 m; Bathypelagic and Abyssopelagic habitats combined).]

[INSERT TABLE 30-1 HERE
Table 30-1: Area, average primary, and fishery productivities for the seven regions.]

30.1.2. Challenges to the Accurate Detection and Attribution of Climate Change-Related Impacts on the Open Ocean

One of the primary goals of Chapter 30 is to assess the extent to which recent literature has successfully attributed detected changes in the world oceans to climate change. Generally, attribution to climate change occurs when the full range of possible forcing factors is considered and those related to climate change are found to be most likely explanation for the change in question. In this regard, a comparison of detected changes to the expectations of well-established scientific conclusions or models plays a central role in the successful attribution of a detected changes to anthropogenic climate change. General approaches and 'best practice' guidelines are discussed in WGII Ch. 18 as well as several other places [*Hegerl et al.*, 2010; *Hegerl and Zwiers*, 2007; *Stott et al.*, 2010].

There are numerous challenges to detecting and attributing change within the world's oceans to climate change. The fragmentary nature of ocean observing, uncertainty of model projections, and confounding influences of non-climatic anthropogenic factors represent significant challenges [*Hoegh-Guldberg et al.*, 2011a; *Parmesan et al.*, 2011]. The latter is further complicated by the fact that drivers arising from local as well as global sources of non-climate related anthropogenic stressors (e.g. pollution, introduced species, overexploitation of fisheries, and disease [*Crain et al.*, 2008; *Halpern et al.*, 2009a; *Halpern et al.*, 2009b; *Halpern et al.*, 2008b] can have a significant influence in most regions. These non-climate change factors may interact synergistically or antagonistically with each other and climate change, making it difficult to distinguish changes due to climate change as opposed to non-climate change factors

The task of detecting the 'fingerprint' of forcing arising from climate change is made even more difficult by the substantial variability that operates at seasonal, interannual, decadal or longer time scales across marine ecosystems [*Stenseth and Mysterud*, 2002; *Stenseth et al.*, 2002]. The El Niño - Southern Oscillation (ENSO) cycle, for example, plays a major role across ocean basins and includes a warm phase (El Niño) and a complementary cool phase (La Niña), operating at a multi-year scale and driving regional marine ecosystem dynamics [*McPhaden et al.*, 2006; *Philander*, 1999]. Similar long-term patterns operate in other regions of the planet (e.g. North Atlantic oscillation). At longer timescales, cycles such as the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO) significant influence marine populations and ocean regions [*Mantua and Hare*, 2002; *Sundby and Nakken*, 2008]. There is considerable discussion as to whether or not changes in global temperature are influencing the frequency and intensity of these climate modes (WGI Ch3). There are two distinctive features associated with the sources of largely natural variability. The first is the linkage between the spatial and temporal scales of various phenomena where modes of longer periodicities are associated with larger spatial periods (Figure 30-2, e.g. [*Dickey*, 1992; *Trenberth*, 2005]. The second is that ocean phenomena in different regions interact through interregional teleconnections. The latter can lead to large-scale wave phenomena and oscillations between climate systems located in geographically separate regions of the ocean (e.g. [*Sundby and Drinkwater*, 2007]. In this regard, an in-depth understanding of the long-term cycles of change within the ocean must be carefully evaluated in any attempt to detect and attribute observations within marine systems to climate change.

[INSERT FIGURE 30-2 HERE
Figure 30-2: Spatial and temporal scales of climate-related phenomena within the world oceans (AMO: [*Sutton and Hodson*, 2005]; NPI: [*Deser et al.*, 2004]; NAO: [*Hurrell and VanLoon*, 1997]; NPGO: [*Di Lorenzo et al.*, 2008]}). The dotted line indicates the circumference of the Earth.]

30.2. Major Conclusions from Previous Assessments

An integrated assessment of the impacts of climate change on oceans at a regional scale was not done by previous IPCC assessment reports, although a chapter devoted to the oceans in the SAR did "attempt to assess the impacts of projected regional and global climate changes on the oceans [*Ittekkot et al.*, 1996]. Notwithstanding, attempts to detect and attribute the impact of climate change on observed changes in ocean and coastal systems were spread among a variety of chapters in previous assessment reports, losing an important opportunity to synthesize the physical, chemical and biological changes occurring within distinct oceanic regions. The fourth assessment report (AR4) concluded, however, that while terrestrial regions are warming faster than the oceans, the average temperature of the global ocean has increased down to depths of at least 3000 m (although most of the warming so far affects only the upper 1000 m of the oceans). Because of the oceans' large thermal inertia (compared to the atmosphere), the global ocean has absorbed over 90% of the heat added to the climate system as a result of increasing greenhouse gas concentrations (SPM, WGI).

Previous assessments observed increasing sea levels due to the thermal expansion of the ocean and water added from melting of glaciers and ice sheets. These changes to ocean temperature and density also have the potential to alter ocean circulation. AR4, however, concluded with respect to the Meridional Overturning Circulation (MOC) or Thermohaline Circulation that "it is very likely that up to the end of the 20th century the MOC was changing significantly at interannual to decadal time scales" (WGI, CH5, Box 5.1), although definitive evidence of a slowing MOC was lacking. Rising atmospheric CO_2 has produced "a decrease in surface pH of 0.1 over the global ocean, which was calculated from the estimated uptake of anthropogenic carbon between 1750 and 1994 [*Raven et al.*, 2005; *Sabine et al.*, 2004]". The influence of rising atmospheric CO_2 varies geographically, with the lowest decrease (DpH = -0.06) in the tropics and subtropics, and the highest (DpH = -0.12) at high latitudes, which is consistent with the reduced buffering capacity of the high latitudes compared to the low latitudes [AR4, 5.4.2.3]. These calculations have been verified by field measurements (AR4, WGI). According to AR4, "sea-level rise over the last 100 to 150 years is probably contributing to coastal erosion in many places" including the east coasts of the United States and

United Kingdom (AR4, WGI). Large-scale trends in ocean salinity were also observed from 1955 to 1998, which were “characterised by a global freshening in sub-polar latitudes and salinization of shallower parts of the tropical and subtropical oceans”. In this case, freshening was observed in the Pacific, while salinity has increased in the Atlantic and Indian Oceans (AR4, WGI, and ES). These changes in surface salinity are qualitatively consistent with that expected from known changes in surface freshwater flux.

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

Observed changes in marine ecosystems and managed fisheries include: changes to plankton community structure and productivity, pelagic phenology and biogeography, intertidal communities along rocky shores, kelp forests, modifications to the geographic range of pathogens and invasive species, changes to coral reefs through increased coral bleaching and mortality, modifications to fish populations and biogeography, modifications to the migratory patterns and trophic interactions of sea birds, marine reptiles and mammals, and general changes in marine biodiversity and ecosystems (AR4, WGII, Table 1.5). While parts of the ocean ecosystem (e.g. [*Sarmiento et al.*, 2004] have received considerable attention, the implications of climate change throughout the open ocean have not been comprehensively assessed.

30.3. Regional Changes in Ocean Conditions

In addition to the warming and expansion of the world’s oceans, increasing concentrations of atmospheric CO_2 have also altered the chemistry of ocean waters (*very high confidence*, WGI Chapter 3). The observed changes in heat content, sea level, biogeochemistry and salinity are consistent with the increased flux of CO_2 and heat into the ocean interior (AR5, WGI, Executive Summary). Changes were examined over the last 30-60 years using established environmental archives (e.g. HadISST 1.1: sea surface temperature data in monthly 1° area grids, for 1870 to present) to explore changes in key environmental variables on a regional basis. The trends within the HadISST 1.1 dataset used here are similar to other data archives and was the principal dataset used during the IPCC 4th assessment [*Trenberth et al.*, 2007].

30.3.1. Physical Changes

30.3.1.1. Heat Content and Temperature

The heat added to the ocean has resulted in an increase in ocean temperature, which is largest in the upper 75 m of the ocean (> 0.1°C per decade, (WGI, CH3, Box 3.1). Understanding of changes in the deep ocean is less certain although there is robust evidence that deep ocean basins are warming at slower yet significant rates (up to 0.05°C per decade, WGI CH3).

Many ocean regions have warmed significantly over the period 1950-2009 (Table 30-2). Analysis of temperature changes within the High Latitude Spring Bloom Systems was hampered by variation in sea ice, which led to distorted measures of the rate of change in sea temperature within these regions. In addition, overall rates of warming were only significant with respect to High Latitude Spring Bloom Systems within the Indian Ocean ($0.092°C.decade^{-1}$). Among the Eastern Boundary Currents, the Californian and Canary currents exhibited significant warming ($\sim 0.10°C.decade^{-1}$), while the Benguela and Humboldt currents did not show significant temperature changes. Warming has not been gradual in most cases, with warming occurring particularly around

1976/77. The Western Boundary Systems showed highly significant warming in the Indian and Western Pacific (0.10°C.decade^{-1} and 0.13°C.decade^{-1}, respectively). All Subtropical Gyres showed significant warming, with temperature increasing at rates that are consistent with analyses done over shorter periods (e.g. 1998 to 2010 [*Signorini and McClain*, 2012] (Figure 30-12B). Trends from 1950-2009 were not significant within the five semi-enclosed seas analyzed here, although studies done of shorter periods (e.g. 1982-2006, [*Belkin*, 2009]) report significant increases in temperature of: Baltic (1.35°C), Black (0.96°C), Red (0.74°C) and Mediterranean Seas (0.71°C). Trends calculated over similar shorter and more recent periods show similar trends and geographic patterns, with most areas of the ocean showing rates of change up to 0.15°C.decade^{-1} and a smaller number of areas (especially at higher latitudes and in the Eastern Boundary Currents) showing cooling (Figure 30-3A).

[*Burrows et al.*, 2011] calculated the rate at which isotherms are migrating by calculating the ratio of the rate of temperature change (°C.year^{-1}) and the spatial gradient of temperature (°C.km^{-1}). This calculation is important biologically given that the speed of movement of isotherms ultimately determines the speed at which populations must either move or adapt genetically to changing sea temperatures [*Burrows et al.*, 2011; *Hoegh-Guldberg*, 2012]. This analysis reveals that isotherms are moving at high velocities (up to 20 km.yr^{-1}) across the ocean surface, especially at lower latitudes (Figure 30-3B; high confidence). Other regions showed lower velocities with contracting isotherms (cooling) in some areas (e.g. the Central and North Pacific, and Atlantic, Oceans Figure 30-3B). There is also robust evidence of changes in the timing of seasonal temperature in both spring and fall/autumn (Figure 30-3 C, D). The timing of spring conditions has advanced by 2-5 day.decade^{-1} in many parts of the global ocean, although the extent of change varies geographically. These changes are likely to have impacts on range of different biological processes including the migration of species to higher latitudes and the timing and synchrony of reproductive and other seasonal behaviors [*Burrows et al.*, 2011; *Hoegh-Guldberg and Bruno*, 2010; *Poloczanska et al.*, 2012].

[INSERT TABLE 30-2 HERE

Table 30-2: Net changes in Sea Surface Temperature (and rate of change) for the period 1950-2009 for key components of the six ocean regions explored in this chapter. Data were obtained from the Hadley Centre (HadISST 1.1). Also shown are data for 4 key coral reef regions. Statistical significance (Simple linear regression) is indicated (*** $p< 0.001$; ** $p< 0.01$ * $p< 0.05$) – the rest are not significantly different from zero. Missing values indicated by '---' due to artifacts and arising from intermittent sea ice (NB reader: to be resolved by next draft; SOD).

[INSERT FIGURE 30-3 HERE

Figure 30-3: Analysis of data from Hadley Centre (HadISST 1.1) for different ocean regions. A. Rate of change in sea surface temperature over the past 30 years (°C. decade^{-1}). B. Velocity at which isotherms are moving (km.decade^{-1}) from 1960-2009. C. Shift in seasonal triggers (days.decade^{-1}) for April and D. for October.]

Significant excursions of sea temperature above long-term summer temperature maxima (or below long-term temperature minima) have significant impacts on marine organisms and ecosystems [*Bensoussan et al.*, 2010; *Crisci et al.*, 2011; *Harley*, 2011; *Hoegh-Guldberg*, 1999]. Consequently, calculating heat stress as a function of exposure time and size of a particular temperature anomaly has proven useful in understanding recent changes to organisms and ecosystems (Section 6). 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 sea surface temperature (SST) was used to define the thermal threshold, above which accumulated thermal stress was calculated as 'exposure time multiplied by stress' or Degree Heating Months (DHM). Thermal stress was calculated as the running total of four consecutive months. While most regions of the ocean experienced an accumulation of heat stress (relative to a climatology based on the period 1985-2000), equatorial and high latitude regions in the Pacific and Atlantic oceans have the greatest levels of the accumulated heat stress (Figure 30-4A). There was a greater number of years that had at least one stress event (DHM > 1) in the last 30 years (1981-2010) than in the preceding 30 years (1951-1980; Figure 30-4 B,C). In the last 30 years, most regions that have coral reefs have experienced heat stress sufficient to cause mass coral bleaching [*Strong et al.*, 2011] events to occur every 2-3 years. These changes are part of a long-term trend in heat stress (AR5 WGII CH30 SOM Fig 1).

[INSERT FIGURE 30-4 HERE
Figure 30-4: Recent changes in thermal stress calculating using HaddISST 1.1 data. (A) Total thermal stress for the period 1981-2010, calculated by summing all monthly thermal anomalies for each grid cell. (B) Proportion of years with thermal stress, which is defined as any year that has a thermal anomaly, for the periods 1951-1980 and (C) 1981-2010. Monthly anomalies were calculated using the maximum in the monthly climatology for each grid cell for the period 1985-2000 after Donner et al (2007).]

30.3.1.2. Sea Level

Measurements from satellite altimetry and tidal gauges show that global mean sea level rise increased at the rate of 3.2 mm.yr^{-1} since 1993 (high confidence, WGI Ch13-3). Patterns of sea level rise vary geographically, with some of the highest rates in the Eastern Indian and Western Pacific Oceans (AR5, WGI, Figure 3.11 and FAQ 13.1, Figure 1). Impacts include increasing penetration of storm surge into coastal areas, changing patterns of shoreline erosion as well as the inundation of saltwater into coastal areas. These changes are likely to impact coastal ecosystems such as beaches, salt marsh, coral reefs and mangroves (see WGII, Ch 29), especially where rates of sea level rise are highest (e.g. South East Asia and the Western Pacific). It is important to point out that not all regions are facing rapid sea level rise. In the eastern Pacific, for example, sea levels have been constant or have been decreasing across large parts of the Americas (AR5, WGI: Figure 3.11 and FAQ 13.1, Figure 1).

30.3.1.3. Winds and Water Movement

Surface winds (Figure 30-5A) have changed over the past 60 years with potential consequences for coastal and oceanic conditions (Figure 2.38, WGI Ch2; Figure 3.8, WGI Ch3), particularly mean significant wave height (Figure 3.9, WG1 Ch3-3), upwelling intensity and depth of water column mixing (see sections 30.5.2 and 30.5.4). Satellite measurements of surface wind speed (beginning in 1987) reveal a decrease in wind speed over the Pacific subtropical gyres and to a lesser extent in the Atlantic subtropical gyres (WGI CH2, Figure 2.38). At the same time, winds speeds have increased within the Eastern Boundary Systems (potentially driving greater upwelling) as well as south of 40°S and across the Bering Sea. Changes to wave height (Fig X WG1 Chp 12) and ocean currents have been observed that are largely consistent with changes to wind speed (WGI Chp 3). The altered wind regime affects Mixed-Layer-Depth (MLD) and upwelling intensity in highly productive regions of the world's oceans (WGII Chp 6). A progressive migration of the westerlies towards higher latitudes was observed during the past two to three decades [*Cai*, 2006.; *Cai and Cowan*, 2007]. The transport of Indian Ocean waters into the South Atlantic has increased in response to latitudinal shifts in the Southern Hemisphere westerlies [*Bard and Rickaby*, 2009; *Biastoch et al.*, 2008a; *Biastoch et al.*, 2008b], with potential implications for the evolution of the MOC [*Friocourt et al.*, 2005] and consequently future climate. Surface wave height has increased over the North Pacific since 1990 and the North Atlantic since the 1950s. In a similar fashion, this trend has held over the past two decades for regions south of 45°S. Extreme wave heights have increased over the past 60 years (likely, WGI CH6).

[INSERT FIGURE 30-5 HERE
Figure 30-5: Absolute change from 1951-2010 in (A) Wind Speed as the absolute change in m.s^{-1}; (B) Solar radiation as change at the surface of incoming solar insolation in Wm^{-2}; (C) Cloud Cover as the absolute change in total cloud fraction (i.e. If at the beginning of the period the cloud fraction was 0.6 and 0.5 at the end of the period, the change would be -0.1) using NCEP re-analyzed data (www.esrl.noaa.gov); and (D) Salinity as the percentage change from 1960-2010 [*Durack and Wijffels*, 2010].]

30.3.1.4. Solar Radiation

Global surface solar radiation decreased 4.3 W.m^{-2}decade^{-1} from the 1950s until 1991 after which it increased at 3.3 W.m^{-2}decade^{-1} until 1999 [*Ohmura*, 2009; *Wild*, 2009]. Changes in solar radiation from 1951 to 2010 vary regionally (Figure 30-5B). The largest increases in solar radiation occurred in the central Pacific and the largest decreases occurred in the temperate Indian, Pacific and Atlantic Oceans (high confidence). Seen over both land and oceans

[*Wild*, 2009] the change in global surface solar radiation has been attributed to decreases in aerosol optical depth and cloud cover (Figure 30-5C, (WG1 Ch3). Changes in cloud cover and solar radiation were correlated with broad changes in surface ocean salinity as a result of associated changes in cloud, rainfall and surface ocean heating.

30.3.1.5. Storms

Higher sea temperatures and specific humidities potentially contribute to fewer yet more intense and damaging storms [*Bengtsson et al.*, 2009; *Grinsted et al.*, 2010]. Models project that the number of extra-tropical and tropical storm events are likely to decrease while average storm intensity is likely to increase [*Bengtsson et al.*, 2006; *Bengtsson et al.*, 2009; *Knutson et al.*, 2010a; *Landsea et al.*, 2010], especially in the Western Atlantic, north of 20°N [*Bender et al.*, 2010].

30.3.1.6. Thermal Stratification

Increases in surface water column heat content have resulted in a 4% increase in thermal stratification (0-200 m, 43 year record, WGI CH3). Increasing thermal stratification is reducing ocean ventilation and the depth of mixing throughout all ocean regions (WGI Ch3 p3-3). This in turn reduces the availability of inorganic nutrients and consequently limits primary productivity. This is particularly important within areas such as the subtropical gyres which dominate the three major ocean basins (see section 30.5.5). These trends may not hold some areas such as the subarctic North Pacific [*Whitney*, 2011].

30.3.2. Chemical Changes

30.3.2.1. Surface Salinity

Sea surface salinity has changed over the past 50 years, with increases and decreases within the range of ± 1.9% (Figure 30-5D). There is robust evidence that surface salinity has increased in the Atlantic Ocean over the past 50 years, with especially rapid increases off west Africa and the eastern Caribbean (Figure 30-5D; high confidence). The salinity of the subtropical gyres in the Pacific, Atlantic and Indian Oceans has also increased. In contrast, the East, North and West Pacific Ocean along with parts of the Gulf of Mexico show some of the strongest freshening trends (high confidence).

30.3.2.2. Ocean Acidification

Increases in atmospheric CO_2 have increased the flux of CO_2 flux into the ocean at sites dependent on a number of variables including temperature. Overall, however, increased atmospheric CO_2 has resulted in a growing inventory of inorganic carbon within the world's oceans. This effect is notably highest in cooler regions. The major processes determining the magnitude of CO_2 flux and its distribution in the ocean are atmosphere-ocean heat exchange, the biological pump, and ocean circulation (WG1, Ch3, Box 3.2). CO_2 flux into the ocean varies geographically, being greatest at high latitudes, particularly in the North Atlantic. The flux of CO_2 in the ocean has also resulted in significant changes to the concentration of important ions such as hydrogen, carbonate and bicarbonate ions. Surface ocean pH has declined as a result of ocean acidification by approximately 0.1 pH units (WG1, Ch3, Box 3.2), intensifying the already naturally lower pH conditions associated with upwelling regions such as those of the west coasts of equatorial Africa as well as North and South America (Figure 30-6A). The saturation states of important forms of calcium carbonate (e.g. calcite and aragonite) are highest at the equator naturally (Figure 30-6B).

[INSERT FIGURE 30-6 HERE
Figure 30-6: Surface ocean pH and aragonite saturation state at different atmospheric CO2 levels simulated by the University of Victoria Earth System Model. The fields of pH and aragonite saturation state are calculated from the

model output of dissolved inorganic carbon concentration, alkalinity concentration, temperature, and salinity, together with the chemistry routine from the OCMIP-3 project (http://www.ipsl.jussieu.fr/OCMIP/phase3).]

30.3.2.3. Oxygen Concentration

Dissolved oxygen is a major determinant of the distribution and abundance of marine organisms (WGII, CH6). Oxygen varies across the ocean basins, tending to be lower in concentration in the eastern portion of the Pacific and Atlantic oceans, and in the northern areas of the Indian Ocean (Figure 30-7). Areas of low O_2 concentrations in deep water are expanding in many parts of the world (WGI Ch3) with impacts on marine life including mass mortality and subsequent exclusion of fish and other metazoans from expanding "dead zones" (high confidence [*Diaz and Rosenberg*, 2008](WGII Chp 6). These areas are rapidly expanding due to a number of regional human drivers not directly related to climate change (i.e. eutrophication of coastal areas) to drivers that are (i.e. increasing sea temperature, increasing stratification and reduced ventilation). The development of hypoxic conditions over recent decades has been documented across a wide array of ocean regions including semi-enclosed seas (Black and Baltic Seas), the Arabian Gulf, and the California, Humboldt and Benguela current systems (Figure 30-7), where eruptions of hypoxic and sulfide-laden water have occurred [*Weeks et al.*, 2002]. In the Atlantic Ocean, the critical regions are centered on 10ºN and 10ºS of the equator. More localized seasonal hypoxic zones have emerged in economically valuable coastal and enclosed seas, like the Gulf of Mexico [*Rabalais et al.*, 2010; *Turner et al.*, 2008], the Baltic Sea [*Conley et al.*, 2009] and Black Sea [*Kideys*, 2002; *Ukrainskii and Popov*, 2009], in connection with nutrient fluxes from land. Over a vast region of the Eastern Pacific stretching from southern Chile to the Aleutian Islands, the minimum pO_2 threshold (< 2 mg.l^{-1}) is found at only 300-m depth and upwelling of increasingly hypoxic waters is well documented [*Grantham et al.*, 2004]. Hypoxic waters in the northern Arabian Sea and the Bay of Bengal are located close to continental shelf depths. Long-term measurements are revealing that oxygen concentrations are declining in these waters, with strong evidence that economically important mesopelagic fish populations are being threatened [*Koslow et al.*, 2011]. The Atlantic Ocean differs from the Pacific and Indian Ocean. Hypoxic conditions are here largely limited to the regions at and adjacent to the two eastern boundary upwelling ecosystems.

[INSERT FIGURE 30-7 HERE
Figure 30-7: Map of the depth [*Hofmann et al.*, 2011] at which a critical value of partial pressure of O_2 of 60 matm occurs which is widely accepted as threatening to marine life on continental shelves (200m depth). Conventional maps of oceanic oxygen values report simple mass properties with no temperature or depth dependence; a better rendition of the availability of O_2 to marine life is provided by the partial pressure, which includes the temperature terms. The value of pO_2 equal to 60 matm reasonably follows the widely used limiting concentration value of 61 μmolar, or 2 mg O_2/l^{-1}. Critical regions in the eastern and northern Pacific and in the northern Indian ocean stand out. In these areas quite modest upward expansion of the depth at which the critical pO_2 level occurs can have negative effects on major fish populations. Note: not all areas have been included – for example, significant hypoxia in the Gulf of Mexico has not been shown.]

30.3.3. Projected Changes

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

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

[INSERT TABLE 30-4 HERE
Table 30-4: Average absolute change in SST (ºC) for each of the four CMIP-5 Representative Concentration Pathways (RCP). Rates of change were estimated in each 30-year period by fitting a linear regression to each grid cell within each region (Figure 30-1, Table 30-1) and then averaging the results across all grid cells in the region. The net change in Sea Surface Temperature (SST) was calculated by multiplying rates of change by 30 years. The total change from 2010-2099 was calculated by adding the net changes in the three successive 30-year periods up to 2099.]

30.4. Global Detection and Attribution of Regional Changes in Marine Organisms and Ecosystems to Anthropogenic Climate Change

Variability different timescales, from hours to decades, as well as a multitude of non-climate related influences, confound detection and attribution of observed changes within the world's oceans to climate change [*Hegerl et al.*, 2010]. This is compounded by the relative paucity of climate change studies on marine ecosystems compared to those done on land [*Richardson and Poloczanska*, 2008]. The recent rapid increase in the number of studies focused on the impacts of climate change on the ocean since 2006 (AR4; [*Hoegh-Guldberg and Bruno*, 2010; *Poloczanska et al.*, 2012] presents an opportunity to examine and potentially attribute observed changes in ocean systems to climate change.

A global database of 1701 long-term observations of biological responses from the oceans was established that spans ecosystems (coastal to open ocean), latitude (Antarctic to Arctic) and trophic level (phytoplankton to top predators) (Figure 30-8; [*Poloczanska et al.*, 2012]. Studies from the peer-reviewed literature were selected using three criteria: (1) authors inferred or directly tested for trends in biological and climate variables, (2) observations spanned at least 19 years, and (3) studies included data after 1990. Observations were defined as those where the authors of a particular paper assessed the consistency of change in a biological parameter (namely distribution, phenology, abundance, calcification, demography or community composition) with climate change. Each observation was classified as ‘consistent’, ‘inconsistent’ or ‘no change’ with consistency based on the original authors’ interpretation of the biological response to climate change. The database therefore accurately captured consistency for studies that appeared contrary to general expectations with climate change, such as shifts to lower latitudes that were actually consistent with climate change when localised climate were taken into account. For example, the southward expansion of sole *Solea solea* into the southern North Sea [*Engelhard et al.*, 2011] and eastwards expansion of intertidal species along the English Channel [*Mieszkowska et al.*, 2006] reflect winter warming of cold, shallow waters.

[INSERT FIGURE 30-8 HERE
Figure 30-8: (A) Consistency of observed responses to climate change from 1701 single- and multi-species studies showing responses that are consistent with climate change (blue), opposite to expected (red) and are equivocal (yellow). Each circle represents the center of a study area. Where points fall on land, it is because they are centroids of distribution that surround an island or peninsula. (B) Frequency of observations by latitude. (C) Observations from the California Current (D) Observations from the northeast Atlantic (from Poloczanska et al 2012).]

The results of the meta-analysis (Figure 30-9) suggest that climate change is having an impact on species in many different ways across a broad range of taxonomic groups (plankton to top predators). Of the observations that showed a response in either direction, 84% were in a direction that was consistent with climate change (Figure 30-9). Consistency was variable according to taxonomic group (Figure 30-9A), latitudinal band (Figure 30-9B) and biological response parameter (Figure 30-9C). Despite remaining knowledge gaps, especially in equatorial regions and the Southern Hemisphere, it is clear that recent climate change has already had widespread impacts on the organisms and ecosystems in the world's oceans.

[INSERT FIGURE 30-9 HERE
Figure 30-9: Percent of observations consistent with climate change predictions. Mean and standard error of responses by (A) taxa, (B) latitudinal region and (C) response measure show significantly higher consistency than expected from random (dashed line at 50% consistency). Solid line is the mean across all observations. Significance of results is listed next to labels (***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$). Sample sizes are listed to the right of each row.]

The overall mean (± SE) rate of re-distribution for marine biota was 93.7 ± 3.88 km decade^{-1} measured at leading range edges and 15.8 ± 3.88 km decade^{-1} at trailing edges (Figure 30-10A). A previous analysis of species range shifts in the ocean described rates of 190 km.decade^{-1} but in 30% of cases climate change was not the primary cause [*Sorte et al.*, 2010]. Changes in marine distributions in response to climate change in the ocean were much greater than those for terrestrial species. The average rate of change on land was 6.1 km dec^{-1} when calculated across taxa [*Parmesan and Yohe*, 2003] or 16.9 km dec^{-1} calculated across regional taxonomic groupings [*Chen et al.*, 2011]. Similarly, the average advance in spring timing showed advances of 4.3 day.decade^{-1} in the oceans (Figure 30-10B [*Poloczanska et al.*, 2012]), contrasting with 2.8 day.decade^{-1} for predominantly terrestrial species (Parmesan 2007).

[INSERT FIGURE 30-10 HERE
Figure 30-10: Rates of change in (A) phenology (days/decade^{-1}) measured during spring/summer (red) and autumn/winter (yellow); and (B) distribution (km/decade^{-1}) for marine taxonomic groups, measured at the leading edges (red), centers of distribution (black) and trailing edges (yellow). Distribution rates have been square-root transformed; standard errors may be asymmetric as a result. Positive distribution changes are consistent with warming (into previously cooler waters, generally poleward) and negative phenological changes are consistent with warming (generally earlier). Means ± standard error are shown, with number of observations and significance (*$p<0.1$, **$p<0.05$, ***$p<0.01$). From Poloczanska et al (2012).]

Rates of climate change can help to explain both present-day distribution patterns and shifts in biodiversity [*Sandel et al.*, 2011]. Change has been expressed as the speed and direction at which isotherms propagate across the Earth's surface [*Loarie et al.*, 2009] and as the shift in timing of seasonal temperatures [*Burrows et al.*, 2011]. Analyses of global temperature showed similar rates of isotherm migration over land and ocean during the past 50 years, but faster phenological shifts over the ocean (Figure 30-3B [*Burrows et al.*, 2011]. The speed and direction of isotherm migration in the ocean since 1960 [*Burrows et al.*, 2011] varies considerably, with locally fast and slow regions and directions that are often not poleward. Rapid velocities (>50km.decade^{-1}) suggest correspondingly large ecological responses, in the North Sea, the sub-Arctic Pacific and Atlantic, and within 15° of the equator.

[*Poloczanska et al.*, 2012] apply global meta-analysis of the consistency of observed biological change with responses expected due to climate change (Figure 30-9) as an approach to attribution. The results of this meta-analysis are unambiguous and reveal that climate change is causing changes to organisms and ecosystems within the world's oceans (high confidence). Further support for attribution was gained, using subsets of the database, to provide additional evidence of "sign-switching" within studies [*Parmesan and Yohe*, 2003] and also by assessing level of process-based understanding. Coupled sign-switching in biological and climate time series of appropriate temporal and spatial scale provides a diagnostic fingerprint of climate change [*Parmesan and Yohe*, 2003]. These increase the likelihood that climate is the main driver of the response. Numerous examples of sign-switching are contained in the database [*Poloczanska et al.*, 2012]. For example, increasing abundances of tropical and subtropical forams and concurrent declines in temperate and sub-polar species over the 20th century [*Field et al.*, 2006] and opposing growth rate responses in fish populations at the centre and edge of their distribution [*Neuheimer et al.*, 2011]. These matches between temporal and spatial climate trends and biological trends provide strong evidence that environmental variability, and temperature in particular, is the primary driver of observed changes for these biological systems and some of the variability in the environment is due to climate change.

Consideration of the strength of underlying mechanistic understanding also provides support for attribution. Confidence in detection and attribution to climate change was evaluated for each observation within the database [*Poloczanska et al.*, 2012] based on temporal resolution, statistical confidence, and understanding of the processes ([*Poloczanska et al.*, 2012] WGII Chp 18). In general, the capability to detect trends is greater than understanding of pathways by which anthropogenic climate change drives changes by region and by taxa (Figure 30-10). However, 23% of studies do provide some level of mechanistic, process-based understanding of how climate affects a given species or systems, providing a stronger, traceable pathway from climate change to impact on species [*Poloczanska et al.*, 2012].

Consideration of the strength of underlying mechanistic understanding also provides support for attribution. Confidence in detection and attribution to climate change was quantified for each observation within the database [*Poloczanska et al.*, 2012] based on temporal resolution, statistical confidence, and understanding of the processes ([*Poloczanska et al.*, 2012] WGII Chp 18). Confidence in detection increased with time series length, greater data precision and quality, and statistical significance of trends in the biological time series and in local climate time series. Confidence in attribution was high where the robustness between the biological response and change in climate change was statistically shown, where mechanistic understanding is presented and where alternate drivers e.g., exploitation, are taken into consideration. The average scores across taxa, biomes and biological response parameters show, in general, the capability to detect trends is greater than understanding of pathways by which anthropogenic climate change drives changes (Figure 30-11A-C). However, 23% of studies do provide some level of mechanistic, process-based understanding of how climate affects a given species or systems, providing a stronger, traceable pathway from climate change to impact on species [*Poloczanska et al.*, 2012]. On a regional scale, the scientific evidence presented in this Chapter, therefore a larger body of evidence than presented by Poloczanska et al (2012), was evaluated for capability to detect trends and provide traceable pathways to climate change (Figure 30-11D) WGII Chp 18).

[INSERT FIGURE 30-11 HERE
Figure 30-11: Quantitative evaluation of degree of confidence in the detection of change and attribution of observed change to climate change of 1701 of 838 species (Poloczanska et al. 2012) across A. Taxonomic groups, B. Biomes and C. Biological response (modified from O'Connor et al in prep). D. Expert assessment of degree of confidence in detection and attribution across regions and processes (based on evidence explored throughout Chapter 30).]

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

This section explores the impacts, risks and vulnerabilities of climate change in the seven ocean regions defined for this chapter. There is considerable variability from region to region, especially in the extent and interaction of climate change and non-climate change stressors. While the latter may complicate attribution attempts in many regions, interactions between the two types of stresses may also represent opportunities to lessen the overall impact of environmental change on ocean organisms and processes.

30.5.1. High-Latitude Spring-Bloom Systems

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

30.5.1.1. Observed Changes and Potential Impacts

30.5.1.1.1. North Atlantic

The North Atlantic spring bloom system has mostly warmed over the past 50 years, although some areas have cooled (Figure 30-3). Many species in this region are responding to climate change (high confidence). In the North-east Atlantic, 75% of 288 cases of climate-driven change in zooplankton (83 cases), benthos (85 cases), fish (100 cases) and seabirds (20 cases) over the past century are consistent with expectations from enhanced greenhouse warming [*Tasker*, 2008]. Observations encompass both bottom-dwelling and pelagic species, and both exploited and unexploited species [*Tasker*, 2008].

The North Atlantic is one of the most intensively sampled and fished ocean regions globally. Most of the longest and most comprehensive time series used to investigate the ecological consequences of climate fluctuations and fishing are from this region [*Edwards et al.*, 2010; *Poloczanska et al.*, 2012; *Southward et al.*, 2005; *Sundby and Nakken*, 2008; *Toresen and Østvedt*, 2000]. Impacts of strong multi-decadal variability superimposed over long-term climate-driven trends are well observed in the North Atlantic. For example, distinct changes in fauna were associated with a pronounced warming period of 1920-1940 [*Wood and Overland*, 2010] when fish and other fauna moved northward [*Drinkwater*, 2006; *Hátún et al.*, 2009; *Iversen*, 1934; *Southward et al.*, 1995].

A general warming trend, of 0.031 ± 0.006ºC.decade^{-1} since the 1920s is evident in the upper 2,000 m of the North Atlantic Ocean. This is linked to long-term climate change (both anthropogenic and natural), with multi-decadal variability amplifying short-term trends [*Polyakov et al.*, 2010]. Since the 1970s, the Atlantic Ocean has warmed more than any other ocean basin with greatest warming over shallow continental shelf areas such as the southern North Sea and Irish Sea [*Lee et al.*, 2011; *Levitus et al.*, 2009; *MacKenzie and Schiedek*, 2007a; b]. By contrast, areas of the North Atlantic (>50ºN) have cooled over recent decades, although this has been masked at some scales by a strong warming phase of multi-decadal variability (WG1 [*Polyakov et al.*, 2010]). Nearly half of the basin-wide warming in the North Atlantic since the mid-1990s has been driven by global warming, with an equal contribution from the Atlantic Multidecadal Oscillation [*Wang and Dong*, 2010].

Substantial biological impacts have been associated with warming over recent decades, including large-scale modification of the phenology, abundance and distribution of plankton assemblages and reorganization of fish assemblages [*Beaugrand et al.*, 2002; *Edwards*, 2004; *Nye et al.*, 2009; *Richardson and Schoeman*, 2004; *Simpson et al.*, 2011; *Tasker*, 2008]. Differential responses in the timing of peak abundances of plankton functional groups suggest temporal mismatches between trophic levels and reorganization of marine communities [*Edwards*, 2004]. We have high confidence that observed changes in the phenology of plankton groups in the North Sea are in response to regional warming [*Edwards and Richardson*, 2004; *Lindley and Kirby*, 2010; *Lindley et al.*, 2010; *Schluter et al.*, 2010; *Wiltshire and Manly*, 2004; *Wiltshire et al.*, 2008]. From 1958 and 2002, seasonal peak abundances of plankton functional groups advanced by 27 days for meroplankton (temporary members of the zooplankton such as larval fishes and echinoderms), 23 days for dinoflagellates, 22 days for diatoms and 10 days for copepods and other permanent members of the zooplankton [*Edwards and Richardson*, 2004]. By contrast, the overall timing of peak abundances of diatoms in spring and autumn remained relatively static [*Edwards and Richardson*, 2004]. Phenological responses of zooplankton were species-specific with substantial variation within functional groups. For example, the peak maximum abundance of the copepod *Calanus finmarchicus* advanced by 10 days from the 1960s to the 2000s, but it's warm-water con-specific *Calanus helgolandicus* did not advance [*Bonnet et al.*, 2005]. The appearance of larvae of benthic fauna in the meroplankton corresponds to the timing of adult reproductive cycles, so shifts in adult phenology [*Beukema and Dekker*, 2005; *Philippart et al.*, 2003] have implications for biological linkages between benthic and pelagic ecosystems [*Kirby et al.*, 2007; *Lindley et al.*, 2010].

Since 1958, the ranges of some cold-water zooplankton assemblages in the North-east Atlantic have contracted towards the Arctic, and many warm-water zooplankton assemblages (specifically copepods) have replaced them (high confidence), moving up to 1000 km northward [*Beaugrand*, 2009; *Beaugrand et al.*, 2002]. Range expansions and contractions linked to changing climate have also been found in benthic crustaceans, bivalves, gastropods, and polychaetes [*Berke et al.*, 2010; *Beukema et al.*, 2009; *Mieszkowska et al.*, 2007; *Weinberg*, 2005]. For example, the southern range of the common intertidal barnacle *Semibalanus balanoides* in the North-east Atlantic has been moving poleward at a rate of 15-50 km decade^{-1} since 1872, and the change is attributed to reproductive failure as winter temperatures warm [*Southward et al.*, 2005; *Wethey and Woodin*, 2008]. It's warm-water con-specific *Chthamalus montagui* is increasing in abundance to replace the niche vacated by *S. balanoides* [*Poloczanska et al.*, 2008; *Southward et al.*, 1995].

Studies of fish communities from both the North-west and North-east Atlantic show distributional shifts (high confidence), with direction varying among species, as well as shifts to greater depth with warming [*Dulvy et al.*, 2008; *Nye et al*., 2009; *Perry et al*., 2005; *Tasker*, 2008]. In the North Sea, winter bottom temperature has warmed by 1.6°C (1980-2004, [*Dulvy et al*., 2008]). The whole demersal fish community shifted deeper by 3.6 m decade^{-1} over the period 1980-2004, although mean latitude of the whole community did not show net displacement [*Dulvy et al*., 2008]. Within the community, cool-water specialists generally shifted northwards while abundant warm-water species shifted southwards reflecting winter warming of the shallow southern North Sea. Trawl survey data from the rapidly-warming southern North Sea suggests waves of immigration by southern species, such as red mullet (*Mullus surmuletus*), anchovy (*Engraulis encrasicholus*) and sardines (*Sardina pilchardus*), linked to increasing population sizes and warming temperatures [*Beare et al*., 2005; *Beare et al*., 2004a; *Beare et al*., 2004b].

Phenological changes have also been found in higher trophic levels. Egg-laying dates of 10 species of seabird in the western North Sea vary from year to year but some exhibited trends from 1971-2006, with some species laying earlier, some later, and some with no trend [*Wanless et al*., 2009]. For seabirds, phenology is related to food acquisition. Arrival at nesting colonies and egg-laying are delayed where warming has led to decreases in local prey availability. Large pelagic fishes such as juvenile Bluefin Tuna (*Thunnus thynnus*) and Albacore Tuna (*Thunnus alalunga*) take summer feeding migrations to the highly productive North-east Atlantic. Their arrival in the Bay of Biscay from 1967-2005 is earlier as a response to warming and subsequent shifts in prey assemblages [*Dufour et al*., 2010]. The timing of the salmon (*Salmo salar*) spawning migration is later at the southern edge of its distribution in Europe, and is associated with regional warming [*Valiente et al*., 2011], [*Valiente et al*., 2011]. Conversely, the migration of salmon is earlier in populations that return to the northeastern North America, where dramatic declines in stocks have occurred [*Friedland*, 1998; *Friedland et al*., 2003; *Juanes et al*., 2004].

Reorganization of marine communities in the high-latitude North Atlantic is reflected in increased diversity of zooplankton and fish, as more diverse warm-water assemblages extend northward in response to changing environmental conditions [*Beaugrand*, 2009; *Hiddink and ter Hofstede*, 2008; *Kane*, 2007; *Mountain and Kane*, 2010; *ter Hofstede et al*., 2010]. Southern (warm-water) species of fish have increased in abundance on both sides of the North Atlantic (medium confidence) [*Beare et al*., 2005; *Collie et al*., 2008; *Hermant et al*., 2010; *Lucey and Nye*, 2010; *Simpson et al*., 2011]. Fishing and climate change can both exert strong influence on marine ecosystems, and dramatically alter the composition of fish communities [*Benoit et al*., 2008; *Dulvy et al*., 2008; *Link et al*., 2010; *Lucey and Nye*, 2010; *Perry et al*., 2005]. For example, investigations from the 20th century reflect periods of both high and low fishing pressure, revealing the combined role of changing climate and fishing pressure in driving shifts in species richness of demersal fish assemblages in the southern North Sea and English Channel [*Genner et al*., 2010; *ter Hofstede and Rijnsdorp*, 2011]. Responses to both of these pressures are species-specific, however. The role of climate change as a driver of distributional change can be both variable and non-linear. For example, the northward distribution shift in plaice (*Pleuronectes platessa*) in the North Sea between 1913 and 2007 is predominantly driven by warming temperatures while both climate change and fishing play a role in the expansion of sole *Solea solea* into the cool southern North Sea [*Engelhard et al*., 2011].

30.5.1.1.2. North Pacific

The dominant source of variability in North Pacific climate is caused by the annual solar cycle. At longer periods, sub-decadal variability is dominated by ENSO [*Trenberth*, 1990]. Decadal and longer periods of variability are reflected in two principal modes; the Pacific Decadal Oscillation (PDO) with periodicities at both 15-25 y and 50-70 y in sea surface temperature [*Mantua and Hare*, 2002] and the Victoria Pattern [*Bond et al. 2003*][*Bond et al*., 2003] the second mode of SST, or its SSH equivalent, the North Pacific Gyre Oscillation (NPGO). The PDO has been reported to have an anthropogenic component thus confounding statistical approaches aimed at removing natural variability from ecological time-series [*Bonfils and Santer*, 2011]. The interplay of the phases of these modes of variability has strong influence on high-latitude Pacific ecosystems. In the space of three years, the eastern North Pacific fluctuated from one of the warmest years in the past century (2005) to one of the coldest (2008) [*McKinnell and Dagg*, 2010; *McKinnell et al*., 2010]. This rapid swing was accompanied by large changes in primary productivity, zooplankton communities and fish and seabirds [*Batten and Walne*, 2011; *Bi et al*., 2011; *Keister et al*., 2011; *McKinnell and Dagg*, 2010; *McKinnell et al*., 2010].

Periods of broad-scale environmental regime shifts are observed across high-latitude ecosystems in the North Pacific (eastern Bering Sea and Gulf of Alaska) and North Atlantic (Barents Sea and Gulf of Maine): 1976-78, 1987-89 and 1998-99, followed by regime shifts in forage fish: 1979-82, 1988-92 and 1998-2001 indicating of how basin-scale variability such as Pacific Decadal Oscillation and North Atlantic Oscillation can manifest across distinct ecosystems [*Link et al.*, 2009a; *Link et al.*, 2009b; *Overland et al.*, 2008]. Regime shifts in the mid-1970s and late-1980s were also reported in the Kuroshio-Oyashio Extension (KOE) in the north-west Pacific with dramatic changes in pelagic ecosystems and rapid sardine and anchovy stocks [*Chiba et al.*, 2008; *Yatsu et al.*, 2008]. Climate regime shifts are characterized by abrupt reorganization of the ecosystems as dynamic trophic relationships among species alter [*Alheit*, 2009; *Hunt et al.*, 2002; *Litzow and Ciannelli*, 2007; *Litzow et al.*, 2008]. Phenological shifts are observed in the zooplankton communities of the North Pacific in response to decadal climate cycles with distinct changes noted after the climate regime shifts of the 1970s and 1990s [*Chiba et al.*, 2006; *Mackas et al.*, 1998]. In the North-west Pacific, springtime copepod abundance also increased linearly over the period 1960-2002 [*Chiba et al.*, 2006].

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

The Bering Sea region is among the most productive of marine regions, and includes the world’s largest single-species fishery for walleye Pollock *Theragra chalcogramma* [*Hunt et al.*, 2010]. This region has undergone major changes in recent decades as a result of climate variability, climate change and fishing impacts [*Hunt et al.*, 2010; *Jin et al.*, 2009; *Litzow et al.*, 2008; *Mueter and Litzow*, 2008]. Sea surface temperatures have increased at a rate of 0.23°C.decade^{-1} over 1982-2006 [*Mueter and Litzow*, 2008] but since 2006 it has been colder than the long-term average [*Coyle et al.*, 2011]. A study of over 100 years of climate history from analysis of coralline algae from the western Bering Sea region, shows significant warming since the 1950s and more recent freshening related to increasing glacial melt and precipitation on mainland Alaska (high confidence) [*Chan et al.*, 2011; *Halfar et al.*, 2007]. Seasonal sea ice cover strongly influences the Bering Sea ecosystem through regulating the spring bloom and extent of the “cold pool” ; an area of cold water <2°C on the northern Bering Sea shelf that is formed as a consequence of sea ice and is maintained over summer [*Hunt et al.*, 2010]. Seasonal sea ice has declined since the 1990s (to 2006), although there is no linear trend 1953-2006, and the initiation of spring ice retreat over the south-eastern Bering Sea shelf occurred earlier [*Wang et al.*, 2007a; *Wang et al.*, 2007b]. Concurrent with a retreat of the cold pool, bottom trawl surveys of fish and invertebrates show a significant community-wide northward distribution shift and a colonization of the former cold pool areas by subarctic fauna [*Mueter and Litzow*, 2008; *Wang et al.*, 2006a]. Total biomass (mean catch per unit effort) increased dramatically in the northern survey area, including the area around the Pribilof Islands [*Mueter and Litzow*, 2008].

Oceanic waters that are low in oxygen are pervasive at relatively shallow waters of the eastern Pacific Ocean (Figure 30-7). Coastal upwelling along the continental shelf can cause mortality of coastal fishes and invertebrates [*Grantham et al.*, 2004], whereas declines of oxygen concentration at depth in the subtropics are explained by changes in the gyre circulation in response to 20th century climate change. The role of climate change in decreasing the oxygen concentration at higher latitudes remains unclear although changes in ocean mixing and ventilation are likely to be contributing factors [*Deutsch*, 2005].

30.5.1.1.3. Southern Hemisphere

The seasonal peaks in phytoplankton productivity in the southern hemisphere are much less pronounced and of smaller magnitude as those in northern hemisphere high-latitudes [*Yoder et al.*, 1993]. The southern hemisphere high-latitude spring-bloom ecosystem is broadly bounded by the sub-tropical front (STF) and sub-Antarctic front.

Associated with the STF is intense biological activity by bloom-forming coccolithophores (phytoplankton) [*Brown and Yoder*, 1994]. Coccolithophore blooms also occur in the sub-polar North Atlantic and Barents Sea [*Balch et al.*, 2007; *Balch et al.*, 1992; *Holligan et al.*, 1993; *Signorini and McClain*, 2009]. The south-western Atlantic region is influenced by the cold Malvinas Current and warm-water Brazil current [*Matano et al.*, 2010], and supports valuable squid and finfish fisheries over the highly-productive Patagonian shelf region [*Garcia et al.*, 2008; *Romero et al.*, 2006]. The calcifying plankton assemblages play a key role in carbon cycles in the region and the transport of carbon to deep ocean sediments. The coccolithophore *Emiliania huxleyi* has extended its range south of 60° in the south-west Pacific (141-145°E) over the two decades since 1983 [*Cubillos et al.*, 2007]. Although the drivers for this range extension are not clear, it is proposed the extension is facilitated by surface warming or changes in the abundance of grazing zooplankton.

This region is far less studied in relation to climate change impacts, compared to the spring-bloom ecosystems of high latitudes in the northern hemisphere, with the exception of the Tasman Sea (SW Pacific). However, observations from seabird breeding colonies in South Africa and Australia show widespread changes that indicate a role of climate change [*Chambers et al.*, 2011; *Crawford et al.*, 2008] while at-sea observations show shifts in the summer distributions of 12 species of albatrosses and petrels in the southern Indian Ocean, suggesting climate change response [*Peron et al.*, 2010]. Poleward shifts in the extent of foraging ranges of wandering albatross *Diomedea exulans* and improved breeding success, over the past 30 years, are consistent with observed changes in the polar westerly wind field [*Weimerskirch et al.*, 2012]

There is high confidence that the western Tasman Sea has shown enhanced warming since 1900, compared to global temperature trends, driven by changes in large-scale wind-forcing leading to a southward expansion of the South Pacific subtropical gyre and intensifying the southward-flowing East Australian Current (EAC) [*Cai*, 2006; *Hill et al.*, 2008; *Wu et al.*, 2012]. Simulations with IPCC AR4 models suggest both stratospheric ozone depletion and greenhouse forcing contribute equally to the observed trend in wind stress [*Cai and Cowan*, 2007]. Coincident with this warming and intensified EAC, a number of benthic invertebrates, fish and zooplankton are now found further south compared to mid-20th century [*Last et al.*, 2011; *Ling*, 2008; *Ling et al.*, 2008; *Pitt et al.*, 2010]. We have very high confidence that warming has facilitated the establishment of the grazing urchin *Centrostephanus rodgersii* in eastern Tasmania during the late 1970s, with deleterious effects on macroalgal beds [*Banks et al.*, 2010; *Ling*, 2008; *Ling et al.*, 2008; *Ling et al.*, 2009].

30.5.1.2. Key Risks and Vulnerabilities

Risks to High Latitude Spring Bloom Systems include changing basin- and regional-scale ocean circulation affecting the transport of organisms and water masses, primary production with implications for food webs and carbon cycling, changes in distribution, phenology and productivity of species leading to reorganization of ecosystems, ocean acidification and, in sub-polar regions, a loss of seasonal sea-ice.

Primary productivity and timing of the spring bloom in this region are very sensitive to environmental change. The magnitude of planktonic production is important for higher trophic level production. Climate induced changes in stratification strength and mixed layer depth can lead to decreased or increased phytoplankton production [*Behrenfeld et al.*, 2006]. The onset of spring warming within high latitude regions is advancing by 2-2.5 days.decade^{-1} [*Burrows et al.*, 2011]. Alteration of the structure and composition of plankton communities will propagate through food webs because of tight trophic linkages, [*Beaugrand and Kirby*, 2010; *Beaugrand et al.*, 2010; *Edwards and Richardson*, 2004]. Mechanisms are complex and tend to be non-linear but have impacts on ecosystems, fisheries and biogeochemical cycles. Climate shifts can also result in abrupt changes or rapid regime shifts in ecosystems [*Alheit*, 2009]. Climate change in the Gulf of Alaska associated with the 1976/77 PDO regime shift produced a very rapid shift in target species for commercial fisheries [*Litzow et al.*, 2008]. A sudden reorganization of commercial fisheries, with attendant social and economic disruption, is a key risk and vulnerability of ongoing climate change in the region.

Shifts in the distributions of many species in high-latitude spring bloom ecosystems are observed in response warm and cool periods [*Batten and Walne*, 2011; *Drinkwater*, 2009; *Genner et al.*, 2010; *Mueter et al.*, 2009; *Overland et* *al.*, 2010]. In the sub-Arctic, the velocity of isotherm migration (1960-2009) was 2-7 times faster in the ocean than over land, [*Burrows et al.*, 2011]. Strong relationships between plankton abundances and fish recruitment, and fish productivity and thermal regimes, give some indication of how exploited populations may change. Climate change model simulations show global warming could alter the dynamics of the Kuroshio Current and the Kuroshio Extension dynamics over the coming century [*Sakamoto et al.*, 2005] that will alter timing, magnitude and structure of spring-blooms in the western Pacific with implications for pelagic fish production and biogeochemical cycles [*Hashioka et al.*, 2009]. Several studies have applied different approaches to project climate change impacts on fisheries. Generalizing findings across these approaches suggest that catch potential but will increase in the NW Pacific and NW Atlantic and decrease in the NE Pacific and NE Atlantic [*Biswas et al.*, 2009; *Cheung et al.*, 2009; *Cheung et al.*, 2010].

Alteration of thermal regimes and declining seasonal sea ice could produce changes in high latitude ecosystems that exceed those observed during 21st century climate oscillations. Decreases in seasonal sea-ice in sub-polar regions are likely to lead to increases in regional primary productivity and modification of ecosystem structure [*Arrigo et al.*, 2008]. The decline in Arctic sea ice will open dispersal pathways between the North Atlantic and the North Pacific; large numbers of the Pacific diatom *Neodenticula seminae* were found in the North Atlantic in 1999 [*Reid et al.*, 2007]. High latitude regions are also vulnerable to rapid changes in ocean chemistry. Calcifying organisms are expected to show impacts of ocean acidification in this century and the impacts on higher trophic levels are also likely to be substantial although have only been described to a small extent so far.

30.5.2. Eastern Boundary Currents

The Eastern Boundary Currents (EBC) include the California, Peru/Humboldt, Canary, and Benguela. They are highly productive regions of the world's oceans, where primary production may exceed 1,000 g C m^{-2} y^{-1}. This level of productivity is a result of large-scale atmospheric pressure gradients and wind systems which advect surface waters offshore (see Section 30.8.1), to be replaced by cold, nutrient-rich waters upwelled from depth into coastal euphotic zones [*Chavez*, 2011; *Chavez and Messie*, 2009; *Chavez et al.*, 2011]. Nutrient input stimulates primary production from phytoplankton blooms that are transferred to mid and upper trophic levels, resulting in substantial fish, seabird and marine mammal populations. As a result, EBCs are considered "hotspots" of biodiversity [*Block et al.*, 2011]. Moreover, although these provinces comprise <2% of the world ocean area, they contribute nearly 7% of marine primary production (Table 30-1) and more than 20% of the world's capture fisheries [*Pauly and Christensen*, 1995], which in EBCs are dominated by catches of planktivorous sardine, anchovy, and horse/jack mackerel, and piscivorous ground-fish such as hake.

30.5.2.1. Observed Changes and Potential Impacts

The historical importance of EBC fisheries has driven extensive studies of their coupled climate-ecosystem dynamics. Observational time series, however, are generally too short to attribute impacts to climate change in many cases. Like other ocean regions, ECBs are projected to warm under climate change, with subsequent density stratification of the water column [*Levitus et al.*, 2009], and to experience altered wind fields as westerly winds shift polewards. However, cooling is also predicted for EBCs, resulting from wind-driven intensification of upwelling. Observations are equivocal, with considerable variability in warming and cooling both within and among systems [*Burrows et al.*, 2011; *Demarcq*, 2009], see 30.3.1.1 Table 30-2). The California and Canary Currents have warmed by 0.65 and 0.56°C respectively while there has been no significant change in the temperature of the Benguela and Humboldt Currents since 1950 (Table 30-2). These differences may relate differences in the response of coastal wind systems (Figure 30-5A). How climate change is likely to influence ocean upwelling is central to ecosystems and fisheries in the EBC. 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]). Discussion of the various hypotheses for how climate change is likely to affect coastal up-welling is presented in Section 30.8.1.

30.5.2.1.1. Canary Current

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

Most observations suggest that the Canary current is warming at both local [*Demarcq*, 2009] and regional [*Belkin*, 2009] scales since the early 1980s with analysis of HadSST 1.1 data indicating that it has warmed by 0.56°C since 1950 ($p<0.05$; Table 30-2). This coincides with a decrease in wind strength over the past 60 years (Figure 30-5A), which could impact both upwelling and the supply of iron-laden dust from the Sahara [*Alonso-Pérez et al.*, 2011], with potential ecosystem consequences. Primary production in the Canary Current does not show a temporal trend [*Arístegui et al.*, 2009], although the time series used (SeaWiFS) may be too short to detect one [*Henson et al.*, 2010]. There is also substantial interannual to decadal-scale variability in the fish catches in this system, and catch trends (1950-2007) are not consistent with climate change [*Zeeberg et al.*, 2008].

30.5.2.1.2. Benguela Current

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

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

While there has been strong warming in the northern and southern sectors of the system ([*Belkin*, 2009], Table 30-2), upwelling intensification is evident for inshore waters of the south-central Benguela, where SST has cooled at a rate of 0.35–0.55 ºC.decade^{-1} [*Rouault et al.*, 2010]). Analysis of HadSST 1.1 data indicate no consistent change over the entire Benguela region over the past 60 years (Table 30-2) which is probably a consequence of combining regional heating and cooling trends within the Benguela system.

Information on other potential climate-change impacts within the Benguela is sparse. Sea-level rise seems to be similar to the global mean, although it has not been well measured in the Benguela [*Veitch*, 2007]. Similarly, although up-welled water in the northern and southern portions of the Benguela exhibit elevated and suppressed $p\mathrm{CO}_2$, respectively [*Santana-Casiano et al.*, 2009]), the consequences of changing upwelling intensity remain poorly explored with respect to ocean acidification. Finally, while periodic low oxygen and anoxic events in the Benguela are driven largely by natural advective processes, these may be exacerbated by future climate change [*Bakun et al.*, 2010; *Monteiro et al.*, 2008].

Despite the general sensitivity of the Benguela to climate change, there is no published evidence from the system that attributes marine ecological impacts to climate change [*Poloczanska et al.*, 2012]. However, this is probably due to the lack of directed studies as opposed to evidence that climate change is not affecting the ecology. 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 shifts to anthropogenic climate change is lacking.

30.5.2.1.3. California Current

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

The average temperature of the California Current has warmed by 0.65°C since 1950 (simple regression; $p < 0.05$, Table 30-2) and is characterised by large-scale inter-annual and inter-decadal climate-ecosystem variability [*Chavez et al.*, 2003; *Checkley and Barth*, 2009; *Hare and Mantua*, 2000; *McGowan et al.*, 1998]. During an El Nino, coastally-trapped Kelvin waves from the tropics deepen the thermocline, thereby severely reducing upwelling and increasing temperatures from California to Washington [*King et al.*, 2011]. Atmospheric teleconnections to the tropical Pacific alter wind stress and coastal upwelling. Therefore, the ENSO cycle is intimately linked with Bakun's (1990) upwelling intensification hypothesis (see Section 30.8.1). Inter-decadal variability in the California Current stems from variability in the Pacific-North America pattern [*Overland et al.*, 2010], which is influenced by the Pacific Decadal Oscillation [PDO; *Mantua et al.*, 1997] and the North Pacific Gyre Oscillation [NPGO; *Di Lorenzo et al.*, 2008]. The major effects of the PDO and NPGO appear north of 39°N [*Di Lorenzo et al.*, 2008; 2009].

Productivity is driven primarily by "bottom-up" trophic mechanisms [*Fleeger et al.*, 2006; *Ware and Thomson*, 2005], with upwelling, transport, and chlorophyll concentrations showing strong interannual couplings. These, in turn, influence trophic transfer up the food chain, affecting zooplankton [*Hooff and Peterson*, 2006; *Keister et al.*, 2011], forage fish [*Brodeur et al.*, 2008], seabirds [*Abraham and Sydeman*, 2004; *Ainley et al.*, 1995], and marine mammals [*Barlow et al.*, 2008; *Thompson et al.*, 2012]. Ecosystem dynamics are therefore sensitive to and may be strongly masked or accentuated by natural variability. For instance, the distribution for many species of larval fish in the Californian Current is strongly related to natural variability. However, many species are also moving pole-wards over long time-spans, an observation that is consistent with observed warming in the region [*Hsieh et al.*, 2009]. ENSO and PDO-like warming thereby provide important benchmarks of potential ecosystem responses to climate change. However, because large-scale cooling (La Niña) and warming (El Niño) generally alternate in sequence [*Ainley et al.*, 1995], apparent unidirectional change may be relatively short-lived. Despite strong ecosystem responses to climate variability on multiple time scales, observational time series are rarely of sufficient duration to conclusively attribute impacts of global climate change [*Hofmann et al.*, 2011].

30.5.2.1.4. Humboldt Current

The Humboldt Current is the largest of the four EBCs, covering an area larger than the other three combined. It comprises the eastern fringe of South Pacific Gyre, linking the northern part of the Antarctic Circumpolar Current with the Pacific South Equatorial Current. Although the primary productivity (per unit area) is modest compared to that of the other EBCs, the Humboldt Current system has very high levels of fish production. Current catches are in line with a long-term average (since 1960s) of 8 million tons.yr^{-1} (http://www.seaaroundus.org/lme/13/1.aspx) although decadal-scale variations range from 2.5 to 13 million tons.yr^{-1}. While the anchoveta currently contributes

80% of the total catch, they alternate with sardines on a multi-decadal scale, with their dynamics mediated by the approach and retreat of subtropical waters to and from the coast [*Alheit and Bakun*, 2010] in a cycle that does not appear to be due to anthropogenic climate change. Thus, from the late 1970s to early 1990s, sardines were more important [*Chavez et al*., 2003]. The other major commercial fish species are jack mackerel among the pelagic fish, and hake among the demersal fish.

The Humboldt Current has not shown a consistent warming trend in SST over the last 60 years (Table 30-2). Wind speed has increased in the central portions of the Humboldt Current although wind has decreased in its southern and northern regions (Figure 30-5A). The lack of a consistent warming signal may be due to the strong influence of adjacent ENSO activity Primary production is suppressed during warm El-Niño events and amplified during cooler La-Niña phases. These changes affect primary production that propagates through to the higher trophic levels [*Chavez et al*., 2003; *Tam et al*., 2008; *Taylor et al*., 2008]. However, in addition to the trophic impacts, there is also a significant thermal impact directly on the organisms, which varies depending on thermal adaptation window for each species. A 37-year zooplankton time series for the coast of Peru showed no persistent trend in abundance and diversity [*Ayón et al*., 2004], although observed shifts coincided with the shifts in the regional SST. As for the other EBCs, there is lack of studies that have rigorously attempted to detect and attribute changes to anthropogenic climate change, although at least one study [*Gutierrez et al*., 2011] provides additional evidence that the northern Humboldt Current has cooled since the 1950s, a trend matched by increasing primary production. This is consistent the observation that the temperature of the Humboldt Current has not changed significantly over the period from 1950-2009 (Table 30-2). Nevertheless, more than in the other three EBS components, the potential impacts of climate change are strongly masked by the adjacent natural climate phenomena, in this case the ENSO.

30.5.2.2. Key Risks and Vulnerabilities

EBC ecosystems are vulnerable to changes that influence upwelling and mixing (i.e. SST, wind strength and direction), which are fundamental drivers of regional productivity, ecosystem structure and fisheries that provide 20% of the world's fisheries production. However, our understanding of how the upwelling in EBCs is likely to respond to future climate change is incomplete (see Section 30.8.1;WGI, CH3). This is reflected by inconsistent projections from GCM ensembles and the relatively poor match between observations and model outputs for the four EBCs. In the GCM ensembles examined, modest rates of warming (0.22 – 0.91°C) occur within the four EBCs in the near term (2010-2039), so that by the end of the century the difference between RCP8.5 and RCP2.6 is 2.18 - 2.42°C (Table 30-4). The exposure of EBC ecosystems to changes of this magnitude is likely to drive fundamental changes to the abundance, distribution and viability of their resident biota (almost certain) although their nature and direction is uncertain.

While the exact influence of climate change over up-welling intensity is uncertain, it is useful to consider the potential outcome if Bakun (1990) is correct and up-welling is intensified in a warmer world. Increased upwelling intensity presents both potential advantages and disadvantages. First, it is likely to boost primary productivity, which may increase fisheries production regionally. However, elevated primary productivity may lead to decreasing trophic transfer efficiency, thus increasing the amount of organic carbon exported to the seabed, where it is likely to increase microbial degradation and hence deplete oxygen concentrations. 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 A key issue to explore in EBCs is therefore whether upwelling will intensify, and if so, whether the detrimental impacts of upwelling intensification on fish production will outweigh its benefits to primary production. These changes need to be considered together with the many other changes that are likely. As projected atmospheric carbon dioxide concentrations increase, the pH and aragonite saturation of upwelling waters will decrease below 7.7 and 1.6, respectively. Although there is substantial evidence from other systems that these changes are likely to impact the biota of EBCs, a detailed understanding is generally lacking.

30.5.3. Western Boundary Systems

The Western Boundary Systems (WBS) are bordered by equatorial regions and high-latitude spring-bloom systems (Figure 30-1) as well as the western regions of the Pacific, Atlantic and Indian oceans. Within these regions, the WBSs are dominated by powerful currents such as the Kuroshio (Pacific) and the Gulf Stream (Atlantic), and are strongly influenced by the monsoons (e.g. Asian-Australian and African monsoons). The WBS includes the marginal seas of the NW Pacific, Indian, Atlantic and comprises Bohai/Yellow Sea, East China Sea, South China Sea and South-east Asia seas (e.g. The Timor, Arafura, Sulu, and northwest coast of Australia) in the Pacific, and the Arabian Sea, Somali Current system, East Africa coast, small archipelagic states, Mozambique Channel and Madagascar in the Indian Ocean, and the Caribbean Sea and Gulf of Mexico in the Atlantic Ocean.

30.5.3.1. Observed Changes and Potential Impacts

Many of the ecosystems within the WBS are strongly impacted by the local human activities including the overexploitation of fisheries, unsustainable coastal development and pollution. These influences have combined with steadily increasing ocean temperatures and acidity to drive major changes to a range of important ecosystems over the past 50 years [*Halpern et al.*, 2009a; *Halpern et al.*, 2008b]. Understanding the interactions between climate change and non-climate change drivers is the critical part of the detection and attribution process within the WBS. Overall, WBSs have warmed by 0.15-0.81°C since 1950, although changes within the Western Atlantic WBS are not significant over this period. Key regions within the WBS such as the Caribbean and Coral Triangle have warmed by 0.47 and 0.37°C respectively over 1980-2009 (Table 30-2).

30.5.3.1.1. Bohai/Yellow Sea/East China Sea

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

Sea temperatures within the Bohai/Yellow Sea/ ECS increased rapidly since the early 1980s [*Cai*, 2011.; 2006.; *Jung*, 2008; *Lin et al.*, 2005; *Tian et al.*, 2012] as a result of anthropogenic climate change (high confidence). The largest increases in SST have occurred in the ECS in winter (1.96°C, 1955-2005) and Yellow Sea in summer (1.10°C, 1971-2006 [*Cai*, 2011.]. These changes in temperature are closely linked to the weakening of the EAM (e.g. [*Cai*, 2011.; 2006.; *Wang et al.*, 2009], and increasing warmth of the Kuroshio Current [*Qi*, 2010; *Wu et al.*, 2012; *Zhang et al.*, 2011]. At the same time, dissolved oxygen has decreased [*Jung*, 2008; *Lin et al.*, 2005] along with an increase in the size of the hypoxic areas (≤2mg/l) in coastal areas of Yellow Sea/ECS [*Jung*, 2008; *Ning et al.*, 2011; *Tang et al.*, 2009].

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

30.5.3.1.2. South China Sea

The South China Sea is surrounded by continental areas and a large number of islands, and is connected to the Pacific, ECS, and Sulu Sea by several Straits such as Luzon and Taiwan Strait. The region is greatly influenced by cyclones, and influenced 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 important commercial fisheries areas and includes biodiverse coral reefs, mangroves and seagrasses.

The surface waters of the SCS have been warming steadily from 1945-1999 [*Li et al.*, 2002; *Liu et al.*, 2007] with the annual mean SST in the central SCS increasing by 0.92°C (1950-2006 [*Cai et al.*, 2008,], a rate similar to that observed for the entire Pacific WBS over the past 60 years (0.81°C, Table 30-2). Significant freshening in the SCS intermediate layer since the 1960s has been observed [*Liu et al.*, 2007]. The temperature change of the upper layer of the SCS has a significant contribution to the sea level variations which is spatially non-homogeneous with temporal variations [*Cheng and Qi*, 2007; *Li et al.*, 2002].

Separating out the climate change signal from the many other sources of variability (e.g. local human stressors, EAM, ENSO and PDO) within the SCS is inherently difficult. There is mounting evidence, however, that changing sea temperatures have influenced the abundance of phytoplankton, benthic biomass, cephalopod catch and demersal trawl catch in northern SCS [*Ning et al.*, 2008]. Coral reefs and mangroves are important resources within the SCS, but are degrading rapidly as a result of both climate change and non-climate change factors. [*The_Second_National_Chinese_Assessment_Report_on_Climate_Change*, 2011]. Elevated SSTs caused mass coral bleaching of SCS reefs in 1998 and 2007 [*Li et al.*, 2011; *Yu et al.*, 2006]. On the other hand, warming of ocean waters has most likely influenced the establishment of a high latitude coral community in Daya Bay in the northern SCS, although this community has since declined [*Chen et al.*, 2009; *Qiu et al.*, 2010]. Despite their clear importance, the impacts and interactions between climate change and local anthropogenic pressures are not well understood and remain a research priority.

30.5.3.1.3. South-east Asia seas

The South-east Asian seas (SASs) has a complex island and archipelago domain which interacts the westward flow of the North Equatorial current and the Indonesian through-flow (Figure 30-1). A large part of this region is referred to as the 'Coral Triangle' [*Veron et al.*, 2009] and is the world's most biologically diverse marine area and includes parts of Malaysia, Indonesia, Philippines, Timor L’este, Solomon Islands, and Papua and New Guinea.

Sea temperatures increased significantly over the period 1985-2006 [*McLeod et al.*, 2010; *Peñaflor et al.*, 2009] although spatial variation is considerable. Sea levels are rising rapidly within the region, with rates as high as 10 mm yr^{-1} [*Church et al.*, 2006; *Church et al.*, 2004; *Green et al.*, 2010]. Like other tropical areas in the world, coral reefs within Southeast Asian Seas have experienced periods of extended warming and been impacted by extensive mass coral bleaching and mortality events since the early 1980s, the most recent of which occurred in the warm conditions associated with 2010 [*Krishnan et al.*, 2011; *McLeod et al.*, 2010]. While a large part of the decline in coral reefs has been due to rising local stresses (principally destructive fishing, declining water quality, and overexploitation of key reef species), projected sea warming represent an major and potentially insurmountable challenge for these valuable ecosystems [*Burke and Maidens*, 2004; *Burke et al.*, 2002]. Calcification in some key organisms (e.g., corals [*Tanzil et al.*, 2009] has slowed over the past two decades with increased sea temperature and acidity although the cause remains uncertain.

30.5.3.1.4. Arabian Sea and Somali Current

The Arabian Sea and the Somali current are relatively productive being strongly influenced by upwelling and the monsoonal system. Wind-generated upwelling enhances primary production in the western Arabian Sea [*Prakash and Ramesh*, 2007]. Several key fisheries within this region are under escalating pressure from both fishing and climate change. Sea water temperature has increased by 0.18ºC in the Arabian Sea and 0.26 ºC in the Somali current over the period 1982-2006 [*Belkin*, 2009], which is consistent with the overall rate of warming of the Indian Ocean WBS since 1950 (0.59ºC, Table 30-2). Salinity of surface waters in the Arabian Gulf has increased by 0.5-1.0% over the past 60 years (Figure 30-5D) due to increased evaporation from warming seas and contributions from the outflows of the saline Red Sea and Arabian Gulf. As a result of ocean acidification, the aragonite saturation depths in the Arabian Sea and Bay of Bengal are now 100 to 200 m shallower than in preindustrial times [*Feely et al.*, 2004]. More than 50% of oxygen minimum zones (OMZs) and dead zones in the world oceans [*Diaz and Rosenberg*, 2008] occur in the Arabian Sea (Figure 30-7) and Bay of Bengal [*Helly and Levin*, 2004] where, unlike other regions, OMZs have not expanded since the 1960s [*Karstensen et al.*, 2008]. As in other tropical regions, periodic heat stress has driven mass coral bleaching and mortality within this region [*Goreau et al.*, 2000; *Wilkinson*, 2004; *Wilkinson and Hodgson*, 1999]. Shoaling of the aragonite saturation horizon is likely to affect the depth distribution of pteropods in the western Arabian Sea [*Hitchcock et al.*, 2002; *Mohan et al.*, 2006]. The information regarding climate change within this region is poor and suggests that important physical, chemical and biological responses to climate change need to be the focus of further investigation.

30.5.3.1.5. East Africa coast and Madagascar

Oceanic conditions within the East Africa and Madagascar region influence on the coastal conditions associated with Kenya, Mozambique, Tanzania, Madagascar, La Réunion, Mayotte, and three archipelagoes (Comores, Mauritius and the Seychelles). Like the north-west section of the Indian Ocean, sea temperatures are increasing rapidly. Changes in surface salinity vary with the location along the East African coastline.

Periods of heat stress over the past 20 years has impacted coastal coral reef ecosystems with mass coral bleaching and mortality within this region [*Ateweberhan and McClanahan*, 2010; *Ateweberhan et al.*, 2011; *McClanahan et al.*, 2009a; *McClanahan et al.*, 2009c; *McClanahan et al.*, 2007]. Steadily increasing sea temperatures have also produced growth anomalies within long-lived corals [*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 [*McClanahan et al.*, 2007] and benthic fish communities [*Graham et al.*, 2008; *Pratchett et al.*, 2011a; *Pratchett et al.*, 2011b], which is likely to alter species composition of coastal fisheries (WGII, Ch5, Ch6; high confidence)[*Jury et al.*, 2010] with a significant lag between the loss of coral communities and the subsequent changes in the abundance and community structure of fish [*Graham et al.*, 2007]. Attempts to slow these impacts have included the establishment of marine protected areas and changes to fishing management [*Cinner et al.*, 2009; *Jury et al.*, 2010; *MacNeil et al.*, 2010; *McClanahan et al.*, 2008].

30.5.3.1.6. Gulf of Mexico and Caribbean Sea

The Caribbean Sea and the Gulf of Mexico form a semi-contained maritime province within the Western Atlantic. These areas are dominated by a range of activities including mineral extraction, fishing and tourism which provide employment and opportunity for over 100 million people who live in coastal areas of the US, Mexico and a range of other Caribbean nations [*Adams et al.*, 2004]. The Caribbean Sea and the Gulf of Mexico have warmed by 0.50°C and 0.31°C respectively from 1982 to 2006 [*Belkin*, 2009; *Simpson et al.*, 2009; *Strong et al.*, 2011], although warming over 60 years is reduced when the two regions are combined (0.15°C, Table 30-2). This is a probably a function of the fact that warming is spatially heterogeneous with greatest warming occurring in the central Gulf of Mexico, the Loop Current region and the eastern Caribbean Sea. The Caribbean region has experienced a sustained decrease in the aragonite saturation state over the period 1988 to 2007 [*Gledhill et al.*, 2008], which is similar to that reported for other tropical locations [*Broecker et al.*, 1979; *Doney et al.*, 2009; *Nelson et al.*, 2001; *Orr et al.*, 2005].

Sea levels within the Gulf of Mexico and Caribbean Sea have increased at the rate of 2-3 mm yr^{-1} from 1950-2000 [*Church et al.*, 2004; *Zervas*, 2009].

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

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

30.5.3.2. Key Risks and Vulnerabilities

Marine ecosystems within the WBS are sensitive to increasing temperature, although detection and attribution is complicated by the significant influence and interaction with non-climate change stressors. Warming has changed the primary productivity of ocean waters (Bohai/Yellow Sea, ECS) placing valuable ecosystems and fisheries at risk. Other risks include the expansion of hypoxic conditions and associated dead zones in many parts of WBS. Given the impacts on coastal ecosystems and fisheries, these changes increase the vulnerability of coastal communities throughout the WBS. Sea temperatures are rapidly increasing within many parts of the WBS ecosystems, which will continue over the next few decades and century. Projections suggest that sea temperatures are likely to increase in the WBS by 0.47-0.54°C (RCP2.6) and 0.73-0.82°C (RCP8.5) in the near term (2010-2039), and by 0.55-0.75°C (RCP2.6) and 2.97-3.07°C (RCP8.5) by the long term (2070-2099) respectively (Table 30-4). Given the fundamental observed impacts associated with smaller changes in sea temperature (0.15, 0.59 and 0.81°C for WBSs over 60 years in the Western Atlantic, Indian ocean and Western Pacific, respectively, Table 30-2), further changes of 1-3°C are likely to be transformational, driving major changes in ecosystem structure and function. Many fisheries are likely to be greatly impacted if the higher end of these projected changes occurs within the WBS, increasing the vulnerability of millions of people who live in coastal communities and depend directly on fisheries and other ecological goods and services.

Coral reefs are unlikely to survive changes in sea temperature beyond an additional increase of 1°C (Ch5, 6; see Section 30.8.2). Combining the known sensitivity of coral reefs within the Caribbean and Coral Triangle regions [*Hoegh-Guldberg*, 1999; *Strong et al.*, 1997; *Strong et al.*, 2011], with the exposure to higher temperatures are projected under medium (RCP4.5) to high (RCP8.5) scenarios, reveals that both regions are projected to experience levels of thermal stress that cause coral bleaching every 1-2 years by the mid to late part of this century (see Section 30.8.2; Figure 30-1 A,B). The frequency of mass mortality events (DHM > 5) climbs towards events that occur every 1-2 years by mid to end of this century under RCP 4.5 and 8.5. Mass mortality events that impact coral reefs will result in changes to community composition in the short-term (2010-2039)[*Adjeroud et al.*, 2009; *Berumen and Pratchett*, 2006] as well as a continuing downward trend in reef-building coral stocks [*Baker et al.*, 2008; *Bruno and Selig*, 2007; *Gardner et al.*, 2003].

30.5.4. Equatorial Upwelling Systems

The largest upwelling systems are found in the equatorial Pacific and Atlantic oceans (Figure 30-1). Equatorial upwelling is a consequence of the Earth's rotation and Easterly (westward) winds and currents that drive water northwards and southwards at the northern and southern edges of these regions, respectively. As result, cold, nutrient-rich and high CO_2 waters are transported from deep waters into the photic zone, driving high levels of primary productivity. This phenomenon results in a highly productive 'cold tongue' that stretches westward across equatorial regions. The ‘warm pool’ of elevated sea surface height is located beyond the ‘cold tongue’. Productivity and CO_2 fluxes in these regions depend on the boundary between ‘cold tongue’ upwelling and the warm pool, where rich conditions for photosynthesis and growth are to be found.

Inter-annual and inter-decadal modes of variability (e.g. ENSO) dominate equatorial upwelling systems, particularly in the Pacific [*Barber et al.*, 1994; *Christian and Murtugudde*, 2003; *Le Borgne et al.*, 2002a; *Le Borgne et al.*, 2002b; *McCarthy et al.*, 1996; *Mestas-Nuñez and Miller*, 2006; *Pennington et al.*, 2006; *Signorini et al.*, 1999; *Wang et al.*, 2006b]. Upwelling is disrupted during El Niño years when trade winds cease or even reverse. ENSO-periodicity controls primary productivity and influences higher trophic levels with significant impacts on fisheries [*Mestas-Nuñez and Miller*, 2006]. ENSO may affect positioning of the InterTropical Convergence Zone (ITCZ), and consequently habitats, productivity, fisheries, and weather at the edge of the subtropical gyre systems (see 30.5.5). The influence of climate change on the behavior of ENSO and other long-term patterns is uncertain at this point (WGI)

30.5.4.1. Observed Changes and Potential Impacts

In contrast with central and western equatorial regions, SST in eastern regions has warmed significantly (WGI, Ch10; 0.34 and 0.49°C from 1950 to 2009 in the Pacific and Atlantic equatorial up-welling systems respectively, Table 30-2). In the Pacific, spatial variation in SST is related to more frequent El Niño Modoki or Central Pacific El Niño events [*Lee and McPhaden*, 2010]. Sea level rise in the eastern equatorial Pacific has been minimal, with the annual rate of change <1 $mm.yr^{-1}$ since 1950 [*Church et al.*, 2006]. This may be related to an increase in upwelling-favourable winds there (Figure 30-5A; Bakun et al., 2010). Sea surface temperatures within the equatorial Atlantic have warmed faster than those in the Pacific (0.7-1.6°C, 1950-2009), with an associated increase in cloudiness and rainfall and a weakening of upwelling [*Tokinaga and Xie*, 2011] Figure 30-5A-C).

Coral reefs (e.g. Galápagos and Cocos islands) have relatively low species diversity and poor carbonate reef development in the eastern Pacific, largely due to low pH and aragonite saturation of recently-upwelled waters [*Glynn*, 2001; *Manzello*, 2010; *Manzello et al.*, 2008]. Prolonged periods of elevated temperature associated with El Niño have impacted corals, kelps and associated organisms, and induced several possible local extinctions [*Glynn*, 2011]. Since 1985, coral reefs from South America west to the Gilbert Islands of Kiribati have experienced the highest frequency of thermal stress (sufficient to cause bleaching) of all corals in the tropics [*Donner et al.*, 2010]. In 1982/1983, mass coral bleaching and mortality affected most of the reef systems within the eastern equatorial Pacific [*Baker et al.*, 2008; *Glynn*, 1984]. Subsequent canonical El Niño and Central Pacific El Niño events in 1997/8, 2002/3, 2004/5, and 2009/10 triggered mass coral bleaching by adding to the background increases in sea temperatures due to climate change [*Donner et al.*, 2010; *Obura and Mangubhai*, 2011; *Vargas-Angel et al.*, 2011]. Impacts of El Niño may have been magnified by other anthropogenic impacts such as fishing, which has caused significant expansion of grazing sea urchins [*Edgar et al.*, 2010]. Consequently, the confounding influences of ocean warming, the frequency, magnitude, and spatial variation of El Niño events, and fisheries makes interpretation of AGW impacts on coral reefs uncertain.

30.5.4.2. Key Risks and Vulnerabilities

Climate models unanimously project that ENSO will continue to be a major driver of oceanic variability over the coming century and beyond, albeit most probably in a modified form. Consequently, superposition of a warming ocean and future (possibly modified frequency and intensity) ENSO may cause oceanic conditions different from those experienced during past El Niño and La Niña events [*Power and Smith*, 2007]. Temperatures within equatorial upwelling regions are projected to continue to warm (Tables 30-2 and 30-4). For Pacific and Atlantic equatorial upwelling systems, differences between RCPs become clear beyond mid-century, with warming of SST under RCP2.6 being a modest 0.44 and 0.68°C to the much higher changes 2.86 and 2.95°C under RCP8.5, respectively (Table 30-4). Further changes in sea temperature will increase stress and may largely eliminate key marine ecosystems such as coral reefs within the region (see Section 30.8.2). As atmospheric carbon dioxide increases, the pH and aragonite saturation of upwelling waters may decrease further. This may impact marine calcifiers, although these species maybe already adapted to low aragonite and calcite saturation states within this region due to upwelling [*Friedrich et al.*, 2012; *Manzello*, 2010]. A poorly understood yet potentially substantial risk is the possible synergistic interaction between sea temperature and declining pH, especially on a large number of biological processes (WGII, Ch6).

30.5.5. Subtropical Gyres

Subtropical gyres dominate the Pacific, Atlantic and Indian oceans and consist of large stable water masses that circulate clockwise (northern hemisphere) and anticlockwise (southern hemisphere) due to the Coriolis Effect (Figure 30-1, Figure 30-12A). The oligotrophic subtropical gyres represent one of the dominant habitats within the world's oceans, and contribute 22% of the primary productivity of the ocean. Consequently, any change in their extent or productivity is important. A large 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. Chapter 5, Coasts and low-lying areas and Chapter 29, Small islands), region-wide issues and impacts are discussed here given the strong linkages between oceanic and coastal issues.

[INSERT FIGURE 30-12 HERE
Figure 30-12: A. Map of SeaWiFS chl-a climatology. The white polygons define the regions that were analyzed and represent the major regions considered as sub-tropical gyres by Signorini and McClain (2012). B. Time series of anomalies in chl-a and B. Sea Surface Temperature SST for subtropical gyres in North Pacific (NPAC), South Pacific (SPAC), Indian Ocean (IOCE) North Atlantic (NATL) and South Atlantic (SATL) Oceans.]

30.5.5.1. Observed Changes and Potential Impacts

The central portions of the sub-tropical gyres are oligotrophic (Figure 30-12A). Temperatures within the subtropical gyres of the North Pacific (NPAC), South Pacific (SPAC), Indian Ocean (IOCE), North Atlantic (NATL) and South Atlantic (SATL) have increased at the rate of 0.024, 0.0236, 0.0322, 0.0248, and 0.0266°C.yr^{-1} from 1998 to 2010 [*Signorini and McClain*, 2012] (Figure 30-12B). This is higher than, although consistent with, changes seen from 1950 to 2009 (0.051-0.111ºC.decade^{-1}, Table 30-2). Chlorophyll levels have decreased in NPAC, IOCE and NATL by 9%, 12% and 11%, over and above the inherent seasonal and interannual variability from 1998 to 2010 [*Vantrepotte and Melin*, 2011] Figure 30-12 C). Chlorophyll levels did not change statistically in the remaining two gyres (SPAC and SATL; which has been confirmed for SPAC by [*Lee et al.*, 2010]). Further, over the period 1998-2007, median cell diameter of key species of phytoplankton exhibited statistically significant linear declines of about 2% in the North and South Pacific, and 4% in the North Atlantic Ocean [*Polovina and Woodworth*, 2012]. Changes in chlorophyll and primary productivity in these regions have been noted before [*Gregg et al.*, 2005; *Polovina et al.*, 2008] and represent a significant expansion of the world's most unproductive waters. Driven by increased water column stratification and a subsequent reduction in the mixed layer depth (high confidence), these changes reduce the vertical transport of nutrients into the euphotic zone and consequently reduce the rate of primary production by phytoplankton. Changes in sea surface temperature have also been accompanied by changes in average surface wind strength over parts of the subtropical ocean gyres (WGI CH2, Figure 2.38), which reduces ocean mixing and ventilation (high confidence).

30.5.5.1.1. Pacific Ocean subtropical gyre

Pacific climate is heavily influenced by the position of the Inter-tropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ), which are part of the ascending branch of the Hadley circulation. These features are also strongly influenced by inter-annual to inter-decadal climate patterns of variability including the El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO). How ENSO and PDO are likely to change as average global temperatures increase is uncertain (WGI, Ch3, Ch14). The position of both ITCZ and SPCZ vary seasonally [*Lough et al.*, 2011], with a northward migration in the northern hemisphere summer and a southward migration in the southern hemisphere summer. These changes determine the timing and extent of the wet and dry seasons in SPAC and NPAC regions, along with the West Pacific Monsoon [*Ganachaud et al.*, 2011]. Changes to the distribution of warm water also influence the intensity of storm systems such as cyclones (WGI, CH3, moderate confidence). Tropical cyclones are prominent in the Pacific, most notably in the western Pacific, and WBS regions between 10°-40° north and south of the equator. 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]. How these patterns are likely to change is uncertain (WGI, Ch3, Ch11), although increased sea temperature is seen as a major driver of the intensity of storm systems (moderate confidence).

The Pacific Ocean underwent an abrupt shift from cool to warmer sea temperatures in the mid-1970s as a result of both natural (e.g. PDO) and climate forcing [*Meehl et al.*, 2009] (high confidence). This change coincided with an abrupt and significant shift in rainfall observed across the Pacific [*Griffiths et al.*, 2003], especially from 150-180°W. Countries such as the Cook Islands, Tonga, Samoa and American Samoa and Fiji tend to experience drought conditions as the SPCZ (with cooler sea temperatures) moves toward the north-east during El Niño (moderate confidence). The opposite is true during La Niña conditions. The impact of changing rainfall on the countries of the Pacific oligotrophic gyres system is discussed in greater detail elsewhere (WGII, Ch5, Ch29).

Elevated sea temperatures within the Pacific Ocean have caused widespread mass coral bleaching and mortality since the early 1980s [*Baker et al.*, 2008; *Donner et al.*, 2010; *Hoegh-Guldberg*, 1999; *Hoegh-Guldberg and Salvat*, 1995; *Mumby et al.*, 2001]. Bleaching arises due to the breakdown of the symbiosis between reef-building corals and dinoflagellate from the genus *Symbiodinium* in response to elevated sea temperatures causing starvation, disease and mortality among vast communities of corals [*Baker et al.*, 2008; *Hoegh-Guldberg*, 1999] see Box 5-3). Rates of decline in coral cover on coastal tropical reef systems range between 0.5-2% per year depending on the location within the Indo Pacific region [*Bruno and Selig*, 2007; *Hughes et al.*, 2011; *Sweatman et al.*, 2011]. The reasons for this decline are complex and also involve non-climate change related factors (e.g. coastal pollution, overfishing) as well is global warming and ocean acidification. A recent comprehensive analysis of the impacts of coral bleaching and mortality concluded "that bleaching episodes have resulted in catastrophic loss of coral reefs in some locations, and have changed coral community structure in many others, with a potentially critical influence on the maintenance of biodiversity in the marine tropics" [*Baker et al.*, 2008]. Impacts of climate change are complicated by the interaction of warmer sea temperatures (due to the enhanced greenhouse effect) and long-term ENSO and PDO variability. Island nations that line the edge of the SPCZ such as Fiji, Samoa, Cook Islands, Tonga and French Polynesia experience conditions during La Niña periods that can push coastal ecosystems beyond their thermal tolerance resulting in mass coral bleaching and mortality [*Hoegh-Guldberg*, 1999] which is different to patterns seen elsewhere (e.g. Eastern Pacific [*Baker et al.*, 2008; *Glynn*, 1984]. The impacts of increasing sea temperature can be exacerbated by increasing ocean acidification with potential impacts on calcification [*Doney et al.*, 2009; *Hoegh-Guldberg et al.*, 2007; *Kleypas et al.*, 1999] moderate confidence), reef metabolism and community calcification [*Dove et al.*, 2012], and other key ecological processes [*Munday et al.*, 2009; *Portner et al.*, 2007; *Portner et al.*, 2001], WGII Ch6). Increasing sea temperatures and sea level are also likely to influence other coastal ecosystems (e.g. mangroves, salt marsh) in the Pacific although significant gaps and uncertainties exist (WGII, Ch5, Ch29)[*Waycott*, 2007]. *Gilman et al.* [2007] found a reduction in mangrove area with sea level rise, with the observed mean landward recession of three mangrove areas over four decades being 25, 64, and 72mm.yr-1, 12-37 times the observed rate of sea-level rise. Significant interactions exist between climate change and coastal development, where migration shoreward depends on the extent to which coastlines have been modified or barriers to successful migration have been established.

The distribution and abundance of pelagic fish such as tuna is also sensitive to changes in sea temperature. Reduced ocean productivity of the subtropical gyres [*Signorini and McClain*, 2012] [*Sarmiento et al.*, 2004] reduces the flow of energy to higher trophic levels, such as those of pelagic fish and sharks [*Le Borgne et al.*, 2011]. Changes to sea temperature also lead to changes in the distribution of key pelagic fish species 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 Pacific Ocean fisheries. Changes in the distribution and recruitment in response to changes in sea temperature as result of ENSO demonstrate a close association of pelagic fish stocks and water temperature. As a result, populations of key pelagic fishery species are projected to move many hundreds of km east from where they are today [*Lehodey et al.*, 2008; *Lehodey et al.*, 2010; *Lehodey et al.*, 2011], high confidence) with implications for income, industry and food security across multiple Pacific Island nations [*Bell et al.*, 2011; *Cheung et al.*, 2010], WGII, Ch 5, Ch 7, Table 29-3, Ch 29, high confidence). Our understanding of the impacts of reduced oxygen on pelagic fish populations is uncertain although there is a high level of agreement on the potential physiological impacts (WGII, CH6). Those species that are intolerant to hypoxia, such as tuna, will have their depth range compressed, which may reduce their vulnerability to being caught (positively) and overall fisheries habitat and productivity (negatively, [*Stramma et al.*, 2010; *Stramma et al.*, 2011]; high confidence). Despite the importance of these potential changes, our understanding of the full range of impacts is minimal at this point.

30.5.5.1.2. Indian Ocean subtropical gyre

Like the Pacific Ocean, the Indian Ocean plays a crucial role in the global weather patterns with teleconnections throughout Africa, Australasia, Asia and the Americas (e.g. [*Clark et al.*, 2000; *Manhique et al.*, 2011; *Meehl and Arblaster*, 2011; *Nakamura et al.*, 2011]. Increasing sea level, sea temperature, storm distribution and intensity, and changing ocean chemistry drive a series of impacts throughout the Indian Ocean (WGII, Ch29). Coral reef ecosystems in the Indian Ocean gyre system were heavily impacted by record positive sea temperature anomalies seen in the southern hemisphere February-April 1998 [*Ateweberhan et al.*, 2011] high confidence). Coral cover across the Indian Ocean region has declined from 37-39% coral cover in the period 1987 to 1997 to approximately 22% coral cover (1999-2000). Responses to the 1998 thermal stress event varied between regions, with the central Indian Ocean islands (Maldives, Seychelles, Chagos, and Lakshadweep) experiencing major decreases coral cover from 40 to 53% (1977 to 1997) to 7% (1999-2000) immediately after the 1998 event (high confidence). Coral reefs aligning islands associated with southern India and Sri Lanka experience similar decreases in coral cover (45% to 13%). Islands in the South West Indian ocean (Comoros, Madagascar, Mauritius, Mayotte, Reunion, and Rodrigues) experienced much lower impacts (44%, 1977-1997 to 40%, 1999-2000). Recovery from these impacts has been variable with sites such as those around the central Indian Ocean islands exhibiting fairly slow recovery (13% by 2001-2005) while those around southern India and Sri Lanka showing much higher rates (achieving a mean coral cover 37% by 2001-2005; [*Ateweberhan et al.*, 2011]). These impacts on key reef-building species are likely to drive major changes in the abundance and composition of fish populations in coastal areas, and affect other ecosystem services that are important for underpinning tourism and coastal protection (WGII Chapter 5, 29).

Pelagic fisheries that involve tuna and other species are important to many small island states within the Indian Ocean (WGII, Ch7). As with Pacific pelagic fisheries, the distribution and abundance of Indian Ocean pelagic fisheries are vulnerable to changes in sea temperature. The anomalously high sea temperatures 1997-98 (leading to deep mixed layer anomalies) coincided with anomalously low primary production in the Western Indian Ocean and a major shift in tuna stocks within the Indian Ocean [*Menard et al.*, 2007; *Robinson et al.*, 2010], high confidence). Fishing grounds in the Western Indian Ocean were deserted and fishing fleets underwent a massive shift toward the eastern basin, which is unprecedented for the tuna fishery. As a result of these changes, many countries throughout the Indian Ocean lost important tuna related revenue. In the case of the Seychelles in 1998, direct, indirect and induced economic effects of the tuna industry expenditure declined by 58, 26 and 35%, respectively [*Robinson et al.*, 2010]. Observations over the period 1991 to 2007 reveal important interactions between depth of the mixed layer and depressed chlorophyll concentrations. In 2007, tuna fishing revenue was again reduced by strong surface warming, the deepening of the mixed layer, and a modest reduction in primary productivity. These trends highlight the overall vulnerability of tuna fishing countries to climate change, which is similar for many other countries in the other major oceans of the world.

30.5.5.1.3. Atlantic Ocean subtropical gyres

The sea surface temperature and salinity have increased within the subtropical gyre systems of the Atlantic Ocean (Figure 30-12, [*Belkin*, 2009; *Signorini and McClain*, 2012] virtually certain). The velocity of surface winds has also declined over a large portion of the subtropical gyre systems in the Atlantic Ocean (Figure 30-5A, high confidence). These changes have influenced the distribution of key fishery species as well as had impacts on coral reefs in Bermuda [*Baker et al.*, 2008; *Wilkinson and Hodgson*, 1999] and in the eastern Caribbean at the edge of the Atlantic subtropical gyre [*Eakin et al.*, 2010]; virtually certain). Small island nations such as Bermuda, which depend on coral reefs for fisheries and tourism, are highly vulnerable to further increases in sea temperature and decreases in pH and aragonite saturation (WGI Ch5, Ch6; Figure 30-6). Changes in the distribution of warm water and primary production influence the distribution and abundance of fisheries species within the North and South Atlantic gyre systems [*Cheung et al.*, 2009; *Cheung et al.*, 2010; *Lehodey et al.*, 2006] with impacts on fisheries catch rates [*Lenoir et al.*, 2011], especially at lower latitudes (high confidence). While there are models, predictions and examples from other oceans, there are few studies from the Atlantic gyre systems that have documented changes in the distribution of key fisheries (Figure 30-8).

30.5.5.2. Key Risks and Vulnerabilities

The vast subtropical gyre systems of the Atlantic, Pacific and Indian oceans are sensitive to increases in temperature that will lead ultimately to increased water column stratification and reduced primary productivity (high confidence). These changes will increase the vulnerability of changes to distribution and abundance of pelagic ecosystems and fisheries (high confidence), frequency and intensity of mass coral bleaching and mortality (high confidence), and potentially the size of oligotrophic areas within the subtropical gyre systems (moderate confidence). Warming is projected to continue (Table 30-4), with substantial increases in the risk and vulnerability associated with the systems that have been observed to change so far. Under RCP2.6, the world subtropical gyres are likely to increase by 0.27-0.60°C in the near term (2010-2039) and between 0.08-0.92°C by the end of the century (Table 30-4). At the other end of the spectrum, and consistent with the current emission pathway, subtropical gyre systems are likely to be 2.18-3.23°C warmer by the end of the century. These changes in temperature are likely to increase water column stability and reduce the mixed layer depth. It is uncertain how longer term cycles such as ENSO and PDO will change and ultimately influence these trends. If the primary driver is the underlying increase in sea temperatures, then it is likely that the world's most oligotrophic ocean regions will continue to expand with consequences for important ecosystem services such as gas exchange, fisheries and carbon sequestration. The impacts of projected sea temperatures on the frequency of coral bleaching and mortality within two key regions within the subtropical gyre are outlined in see Section 30.8.2. As with other regions dominated by coral reefs, mass coral bleaching becomes an annual event under all scenarios, with mass mortality events beginning to occur every 1-2 years (see Section 30.8.1, Figure 30-18). Coral dominated ecosystems will disappear under these circumstances, especially given the lack of stabilization of climate scenarios under these conditions. The loss of corals has implications for the three-dimensional structure of coral reefs, and the role of the latter as habitat for organisms such as fish [*Hoegh-Guldberg*, 2011; *Hoegh-Guldberg et al.*, 2011b; *Pratchett et al.*, 2011a; *Pratchett et al.*, 2011b]. These changes have serious implications for dependent coastal fisheries and tourism industries [*Bell et al.*, 2011; *Pratchett et al.*, 2011a; *Pratchett et al.*, 2011b]Table 29-3, WGII Ch29, moderate confidence). Changes to sea temperature also have implications for rainfall flux, which is likely to have significant implications for island nations scattered throughout the subtropical gyre systems. This will influence the distribution of cloud (Figure 30-13) and rainfall (Figure 30-14) which will tend to increase at the equatorial and Pacific convergence zones. While much of the sub-tropical gyres will experience drying conditions, large increases in rainfall are projected around these regions.

[INSERT FIGURE 30-13 HERE
Figure 30-13: Change in cloud fraction for each of three CMIP-5 Representative Concentration Pathways (RCP 2.6, 6.0 and 8.5). For each pixel, these plots were derived by calculating the average monthly % cloud cover for the period 2006 – 2035 and subtracting it from the monthly average from 2070-2099. These values represent the

absolute change in total cloud fraction (i.e. if the cloud fraction was 60% in 2006-2035 and 50% in the 2070-2099 period, the change would be a -10% change in average monthly cloud fraction).]

[INSERT FIGURE 30-14 HERE
Figure 30-14: Change in precipitation for each of three CMIP-5 Representative Concentration Pathways (RCP 2.6, 6.0 & 8.5). For each pixel, these plots were derived by calculating the average monthly precipitation (mm/year) for the period 2006 – 2035 and subtracting it from the monthly average from 2070-2099 to provide a measure of the absolute change in precipitation over approximately the next 65 years.]

Ocean pH within the subtropical gyres will continue to decrease as atmospheric carbon dioxide increases, bringing pH within the subtropical gyres to 7.7 (800 ppm) and 7.9 (450 ppm, Figure 30-6A). Aragonite saturation states will decrease to around 1.6 (800 ppm,) and 3.3 (450 ppm, Figure 30-6B). Decreasing aragonite saturation states pose serious risks to marine calcifiers such as coccolithophores [*Doney et al.*, 2009; *Feely et al.*, 2009].

30.5.6. Semi-Enclosed Seas

Semi-enclosed seas represent an important subset of ocean regions, being land-locked and consequently heavily influenced by surrounding continental climates [*Healy and Harada*, 1991]. In many cases, they provide important marine resources that are important to key fisheries and tourism, and hence five major semi-enclosed seas (all over 200,000 km² with single entrances < 120 km wide) are considered here. This particular geography dictates reduced circulation and exchange with general ocean waters, and the sharing of these ocean basins between two or more neighbouring nation states. In many cases, the small volume and disconnected nature of semi-enclosed seas (relative to coastal and oceanic environments) makes them highly vulnerable to both local and global anthropogenic stressors.

30.5.6.1. Observed Changes and Potential Impacts

30.5.6.1.1. Arabian/Persian Gulf

The Arabian Gulf is the world's warmest sea with both extreme negative and positive temperature excursions (annual temperature range, 12-35°C). Like other semi-enclosed seas, its enclosed and landlocked nature is likely to make the Arabian Gulf particularly vulnerable to changing global conditions. Sea temperatures within the northern Arabian Gulf have increased at the rate of 0.6 ± 0.3°C.decade^{-1} (1985 to 2002, [*Al-Rashidi et al.*, 2009]), although the absolute change over longer periods is lower (0.65°C, 1950-2009, Table 30-2). Our understanding of the impacts of these changes on marine ecosystems and human activities within the Arabian Gulf is minimal although some ecosystem components have been explored to some extent. The mass coral bleaching and mortality associated with 1996 and 1998 was a direct result of the sensitivity of reef-building corals to elevated sea temperatures [*Riegl*, 2002; 2003], high confidence, Box 5-3). These changes to coral reefs have resulted in a loss of fish abundance and diversity, with invertivores decreasing in abundance while herbivore and planktivore abundances have increased [*Riegl*, 2002], moderate confidence). Despite organisms there being adapted to the highest sea temperatures on earth, anthropogenic climate change is driving higher frequencies and intensities of mass coral bleaching and mortality [*Riegl et al.*, 2011]. Other biological changes (e.g. harmful algal blooms and fish kills, [*Heil et al.*, 2001]) have been associated with the increasing sea temperatures of the Arabian Gulf although attribution to increasing temperatures as opposed to other factors (e.g., water quality) remains uncertain at this point [*Bauman et al.*, 2010; *Sheppard et al.*, 2012].

30.5.6.1.2. Red Sea

Few studies have focused on attributing recent changes in the Red Sea to climate change and ocean acidification. The Red Sea has warmed by 0.74°C from 1982-2006 [*Belkin*, 2009; *Raitsos et al.*, 2011], high confidence) with at least one study reporting even higher rates (1.5°C since the 1980s [*Cantin et al.*, 2010]. Skeletal growth of the long-lived massive coral *Diploastrea heliopora* has declined significantly (high confidence). [*Cantin et al.*, 2010] demonstrated that growth of the species is negatively correlated with increasing temperature, and based on these trends, these corals will cease to grow by 2070 (moderate confidence) although this may not hold for all coral species (e.g. *Porites* and *Cyphastrea*; Cantin et al., in review, PLosOne). For example, an increase in linear extension of *Porites* corals, beginning in the 1980s was recorded in the northern Red Sea [*Heiss*, 1996], where the present local warming rate is ~0.037ºC y^{-1}, suggesting that these corals are living in sub-optimal (cooler waters) conditions and may still benefit from elevated temperature before reaching their thermal threshold, at which point growth rates would be predicted to decline as they are in many oceans. [*Riegl and Piller*, 2003] concluded that corals at moderate depths in the Red Sea could provide important refugia in the future. *Silverman et al.* [2007] quantified the sensitivity of net coral reef ecosystem calcification to changes in carbonate system chemistry (pH, aragonite saturation). Their results demonstrate a strong negative impact of ocean acidification on ecosystem scale calcification. The sensitivity of ecosystem-scale calcification measured *in situ* is much stronger than that observed for single organisms in tank experiments. These results suggest that small changes in carbonate dissolution arising from ocean acidification associated with a doubling of atmospheric CO_2 concentrations could strongly impact on the long-term persistence of carbonate coral reef systems within the Red Sea [*Silverman et al.*, 2007; *Silverman et al.*, 2009].

30.5.6.1.3. Black Sea

Black Sea temperatures have increased by 0.96ºC from 1982 to 2006 [*Belkin*, 2009] which matches the results of other studies [*Bozkurt and Sen*, 2011; *Buongiorno Nardelli et al.*, 2010] high confidence). [*Buongiorno Nardelli et al.*, 2010] also show that short-term sea surface temperature variability (week-month) appears to be strongly influenced by interactions with the overlying atmosphere and other aspects of this highly landlocked sea. Freshwater discharge from rivers draining into the Black Sea remained more or less constant [*Ludwig et al.*, 2009]. Increased water temperature has steadily eliminated the Cold Intermediate Layer (CIL; with temperatures below 8°C) throughout the Black Sea basin [*Oguz et al.*, 2003], high confidence). Reduced water column mixing and up-welling during warmer winter periods has resulted in a reduced supply of nutrients to the upper layers of the Black Sea [*Oguz et al.*, 2003] and exacerbated low oxygen conditions in the deeper parts of the Black Sea, which is the world's largest anoxic marine basin [*Murray et al.*, 1989], high confidence). These changes have coincided with the collapse of fish stocks and the invasion by the ctenophore *Mnemiopsis leidyi* in the 1980s [*Oguz et al.*, 2008], while at the same time, inputs of nutrients such as phosphate from the River Danube have decreased strongly since 1992-1993. Environmental perturbations explain the declining levels of primary productivity, phytoplankton, bacterioplankton, and fish stocks in the Black Sea from the mid-1990s [*Oguz and Velikova*, 2010; *Yunev et al.*, 2007]. The Black Sea system is highly dynamic and strongly affected by non-climate stressors in addition to climate change, making attribution studies difficult.

30.5.6.1.4. Baltic Sea

The Baltic Sea is also a highly dynamic system with complex responses to global climate change processes. Temperatures in the Baltic have increased by substantially since the early 1980s, with estimates of 1.35°C (1982-2006) being among the highest for semi-enclosed seas [*Aleksandrov et al.*, 2009; *Belkin*, 2009]). Increases if this magnitude are not seen in longer records throughout the Baltic Sea (1861-2001, [*Mackenzie et al.*, 2007]; from 1875, [*Madsen and Hojerslev*, 2009]. The salinity of the surface and near bottom waters of the Baltic Sea (e.g. Gdansk Basin, [*Aleksandrov et al.*, 2009]; central Baltic [*Fonselius and Valderrama*, 2003; *Mollmann et al.*, 2003] decreased from 1975 to 2000, due to changing rainfall and river run-off and a reduction in the pulses of sea water (important for oxygenation among other things) from the North Sea through its opening to the North Sea, Kattegat [*Conley et al.*, 2009; *Hanninen and Vuorinen*, 2011; *Samuelsson*, 1996] high confidence). There is a strong vertical zonation within the Baltic Sea in terms of the availability of oxygen. The shallow regions of the Baltic are relatively well oxygenated. However, oxygen levels are low in the deeper basins of the Baltic Sea, producing conditions where organisms and ecosystems are exposed to prolonged hypoxia.

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

A combination of climate-induced hydrographic changes (i.e. decreased salinity and increased temperatures), eutrophication and overfishing has resulted in major structural changes over all trophic levels (particularly, an ecosystem regime shift [Möllmann et al., 2009]) in the deep basins of the Baltic sea. The strong relationship between primary and secondary production, and hydrography, suggests that major changes in Baltic fisheries production are very likely to occur as temperatures increase and salinities decrease. This has been demonstrated by examples such as that of the commercially important top-predator cod [*Lindegren et al*., 2010](moderate confidence).

30.5.6.1.5. Mediterranean Sea

The Mediterranean Sea is strongly linked to the climates of North Africa and central Europe. Sea surface temperatures within this semi-enclosed sea have increased (+0.5°C from 1985 to 2000 [*Rixen et al*., 2005b]; +0.71°C from 1982 to 2006, which is similar to rates found in monitoring programs across the Mediterranean Sea (e.g. [*Calvo et al*., 2011; *Coma et al*., 2009; *Conversi et al*., 2010]. Rates over longer periods (1950-2009; Table 30-2) are lower 0.59ºC, indicating that longer-term cycles have important influences. In the western Mediterranean Sea, water temperatures, over the past 30–40 years, have also increased at depth [*Bethoux et al*., 1990; *Rixen et al*., 2005a; *Vargas-Yanez et al*., 2010]. Natural cycles such as the Atlantic Multidecadal Oscillation (AMO) and the North Atlantic Oscillation (NAO), can obscure or accentuate the overall warming trend [*Marullo et al*., 2011]. Relatively warm episodes in the 1870–1890s, 1930–1940s and since the 1990s, for example, exhibit an influence of the AMO [*Kerr*, 2000; *Moron*, 2003]. Reported temperature anomalies in the Mediterranean, often locally manifesting themselves as periods of low wind, increased water column stratification and deepening thermocline, are associated with positive phases of the NAO index [*Lejeusne et al*., 2010; *Molinero et al*., 2005]. Sea levels, which are also strongly influenced by NAO phases, have increased rapidly in some areas over the last decades. These rates have been approximately 3.4 mm.yr^{-1} (1990-2009) in the NW Mediterranean [*Calvo et al*., 2011], high confidence). When pooled over longer time-scales, however, these influences are reduced and the rate of sea level rise is lower [*Massuti et al*., 2008]. If the positive phase of the NAO is more frequent in the future [*Kuzmina et al*., 2005; *Terray et al*., 2004], then decreases in sea level during the winter are projected [*Jorda et al*., 2012]. As temperatures have increased, the Mediterranean has become more saline (+0.035 to 0.040 psu over 1950-2000, [*Rixen et al*., 2005b]) and the length of the stratification period persisted twice as long in 2006 than it did in 1974 [*Coma et al*., 2009].

Conditions within the Mediterranean Sea changed abruptly and synchronously with similar changes across the North, Baltic, and Black Seas in the late 1980s [*Conversi et al*., 2010]. These changes in physical conditions (increased temperature, higher sea level pressure, positive NAO index) also coincided with step-changes in diversity and abundance of zooplankton, decreases in fish such as anchovies, and frequency of red tides and mucilage outbreaks [*Conversi et al*., 2010]. Mucilage outbreaks are strongly associated with warmer and more stratified water columns (high confidence), and lead to a greater abundance and diversity of marine microbes and potentially disease organisms [*Danovaro et al*., 2009]. Warmer conditions are also driving the northward spread of thermophilic species (medium confidence) such as the sardine, *Sardinella aurita* [*Sabates et al*., 2006; *Tsikliras*, 2008], and contributed to the fast spread of the coral *Oculina patagonia* [*Serrano et al*., submitted]. The recent spread of warm-water species that have invaded through the Straits of Gibraltar and through the Suez Canal, into cooler northern areas is leading to "tropicalisation" of Mediterranean fauna [*Ben Rais Lasram and Mouillot*, 2008; *Bianchi*, 2007; *CIESM*, 2008;

Galil, 2008; 2011] (high confidence). Warming since the end of the 1990s has accelerated the spread of tropical invasive species from the eastern Mediterranean basin [*Raitsos et al.*, 2010]

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

Long-term data series (> decade) to measure the rate of acidification in the Mediterranean Sea are scarce [*Durrieu de Madron et al.*, 2011]. Recent re-analysis, however, has concluded that the pH of Mediterranean waters has decreased by 0.05-0.14 pH units since the preindustrial period [*Luchetta et al.*, 2010; *Touratier and Goyet*, 2011], medium confidence). Even the deepest Mediterranean water is contaminated by anthropogenic CO_2, which places this region as one of the world’s most acidified [*Touratier et al.*, 2012]. Studies that have explored the impact of this acidification on the biology and ecology of the Mediterranean Sea are largely lacking.

30.5.6.2. Key Risks and Vulnerabilities

Semi-enclosed seas are highly vulnerable to changes in global temperature on account of their small volume and landlocked nature. Consequently, semi-enclosed seas are likely to respond faster than other parts of the ocean. Risks to ecosystems increase as water column mixing is reduced, increasing hyoxia at depth and reducing nutrient supply to the upper water column. The impact of rising temperatures on semi-enclosed seas is exacerbated by their vulnerability to other human impacts such as overexploitation, pollution and coastal run-off. Due to a mixture of global and local human stressors, important fisheries have undergone fundamental changes in their abundance and distribution over the past 50 years. The major risks to the semi-enclosed seas arise from an increasing frequency of temperature extremes that drive mass mortality events, increasing water column stabilisation leading to reduced mixing, and consequent changes to the distribution and abundance of marine organisms. The vulnerability of marine ecosystems, fisheries and human communities associated with the semi-enclosed seas will continue to increase with rising global temperatures.

Sea temperatures within the five semi-enclosed seas are projected to continue to increase rapidly. Under the worst scenario (RCP 8.5; Table 30-4) considered here, sea temperatures are projected to increase by 0.93-1.23°C by 2039 and by 3.59-4.43°C by the end of the century (Table 30-4). The greatest increases are seen in the Black Sea (4.43°C) and Arabian Gulf (4.33°C), with significant yet lower amounts of change in the Red Sea (3.59°C). The heat content added to these small oceans is likely to increase stratification of the water column, which will reduce the nutrient supply to the upper layers of the water column, reducing primary productivity and driving major changes to the structure and productivity of fisheries. Reduced mixing and ventilation, along with increase microbial metabolism, will expand hypoxia and associated dead zones. Changing rainfall intensity is likely to also have strong influences on the physical and chemical conditions within the world semi-enclosed oceans, in some cases combining with climate change to transform these important ocean areas. These changes are likely to increase the vulnerability of semi-enclosed seas such as the Baltic and Black seas to reduced oxygen levels, which are likely to impact important fisheries. Based on responses to temperature extremes seen over the past 30 years, these changes will increase the frequency and intensity of impacts arising from heat stress, such as the mass mortality in the Mediterranean during the Summers of 1999, 2003 and 2006, and the Arabian Gulf in 1996 and 1998. Similar predictions to those seen in Section 30.8.2 can be applied to the coral reefs of the Arabian Gulf and the Red Sea, where temperatures are projected to increase well above known thresholds for mass coral bleaching and mortality.

30.5.7. Deep Sea (>1000 m)

Assessments of the influence of climate change on the deep sea are challenging due to difficulty of access and scarcity of long-term, comprehensive observations [*Smith et al.*, 2009]. The size of this habitat is vast, covering well over 60% of the earth's surface and stretching from top of the mid-oceanic ridges to bottom of deep ocean trenches. The fossil record in marine sediments reveals that the deep ocean environment has undergone large changes due to climate change in the past [*Knoll and Fischer*, 2011]. The paleo-skeletal record shows it is the rate, not simply magnitude, of climate change (temperature, oxygen and carbon dioxide) that is critical to marine life, and that the rate of change today greatly exceeds that of other major events in Earth history. Two primary time scales are of importance. The first is the slow rate (century scale) of ocean circulation and mixing and consequently the slow rate at which deep-sea ecosystems experience physical climate change. The second is the rapid rate at which organic matter enters the deep ocean from primary productivity generated at surface of the ocean, which represents a critical food supply to deep-sea animals [*Smith et al.*, 2009; *Smith et al.*, 2008]. Since the upper ocean is currently experiencing warming, increased stratification, and changing productivity (WGI Ch3; see other sections of 30.5), it is likely that asynchrony is developing between the climate impacts of slow warming at depth and the rapidly changing (decreasing/increasing) food supply to deep-sea animals.

30.5.7.1. Observed Changes and Potential Impacts

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

Temperature accounts for 86% of the variance in the export of organic matter to the deep sea [*Laws et al.*, 2000]. Consequently, upper-ocean warming is likely to reduce the export of organic matter, impacting the distribution and abundance of deep sea organisms and associated food webs and ecosystem processes [*Smith Jr and Kaufmann*, 1999; *Smith et al.*, 2008]. Most organic matter entering the deep ocean is recycled by microbial systems [*Buesseler et al.*, 2007], the metabolism of which are temperature sensitive. Upper ocean warming is highly likely to increase the rate of sub-surface decomposition of organic matter, intensifying the intermediate depth oxygen-minimum zones [*Stramma et al.*, 2008] and reducing food supply to the abyssal ocean.

Quantifying these effects is difficult since complex ecosystem responses are likely and information is sparse. The food supply from sinking particles to the deep sea is about 20% of net primary productivity of ~45 Gt $C.yr^{-1}$, or about 9 Gt $C.yr^{-1}$ [*Laws et al.*, 2000]. If the temperature dependence of models such as that of Laws et al. (2000) is correct, then warming of the upper ocean by 2.5ºC (which is projected to occur under RCP 6.0 and 8.5; Table 30-4) will reduce the fraction exported to the deep sea by about 5%. Warming of intermediate waters will increase respiration at those depths. The temperature dependence is not well known, but is likely to be similar to microbial rates in environments such as soils and sediments with a Q10 of about 2.5 [*Thamdrup et al.*, 1998]. This suggests that a maximum reduction in food supply to the deep sea from 20% to 16% of global net primary production (7.2 Gt C yr^{-1}) is likely to occur under a 2ºC warming of the upper ocean.

Ocean oxygen levels are decreasing in the deep ocean [*Karstensen et al.*, 2008; *Keeling et al.*, 2010; *Stramma et al.*, 2008]. The largest signals occur at intermediate depths shallower than 1,000 m [*Nakanowatari et al.*, 2007; *Whitney et al.*, 2007], but some waters >1,000 m depth are also experiencing decline [*Falkowski et al.*, 2011; *Jenkins*, 2008]. It is certain that the quantity of dissolved oxygen will be reduced with warming due to direct effects on solubility. It is also certain that metabolic demand and microbial respiration rates will increase with temperature [*Brown et al.*, 2004]. Consequently, two changes will have greater impact on oxygen decline than the solubility effect alone (high confidence). Deep-sea waters have relatively high pO_2 due to thermodynamic effects of pressure and will be better oxygenated than the mid waters.

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

30.5.7.2. Key Risks and Vulnerabilities

Rising atmospheric CO_2 poses a risk to deep-water communities by reducing the amount of carbonate ions and by changing ocean pH (high confidence). The reduced flow of organic carbon to some parts of the deep ocean (e.g. subtropical gyre systems) is very likely to impact deep-ocean ecosystems (moderate confidence). Changes in temperature and the supply of organic carbon from surface waters are likely to interact and increase the risk of impacts to deep-ocean ecosystems. As with the deep sea generally, there is an urgent 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.

30.6. Sectoral Impacts, Adaptation, and Mitigation Responses

The ocean supports a wide array of sectors, both in the open ocean and associated coastal waters (WGI Ch5). Discussion is restricted here to economic, environmental and social sectors that have a direct association with the open ocean. Open ocean ecosystems support significant economic sectors including fisheries, tourism, shipping, oil and gas, and renewable energy, as well as non-market values such as biodiversity and ecosystem services. Climate change impacts on ocean sectors will be mediated through simultaneous changes in multiple environmental variables. Many climate change impacts can be avoided, reduced or delayed by mitigation, yet both short-term and longer-term adaptation are necessary to address impacts that result from warming, even under the lowest stabilization scenarios assessed.

30.6.1. Interaction within and between Ocean Regions

Although the ocean was divided into seven major regions for the purposes of the present chapter, the ocean and its responses to climate change involve a highly integrated set of interactions driven by currents, physiochemical interactions, connectivity between weather patterns, and movement of organisms. For example, many wide-ranging species present in the Pacific Ocean are also found in the Indian and Atlantic Oceans, developing wide distributions over long periods, more recently through the transport of organism across the world's oceans by shipping. The large distribution and genetic connectivity of some marine populations contrasts the more limited distributions of terrestrial organisms. It should be noted, however, that this connectivity may be much smaller for some ocean regions (e.g. semi-enclosed seas).

Ocean regions are also linked through global industries, such as fishing and shipping. These sectors, however, rarely interact directly, except through the common use of the open ocean. For sectors such as tourism and fishing that rely on similar natural resources, direct interactions may be more common and can be minimised through coordinated planning and regulation of the sectors. Collaboration among the international community, as with the Coral Triangle

Initiative [*Clifton*, 2009], can also play an important role in reducing conflict and maximising synergies between countries approaching similar problems. Given that resources such as fish stocks are changing their distribution and abundance in response to climate change, international collaboration across ocean regions will become increasingly important [*Cheung et al.*, 2010; *Lehodey et al.*, 2006].

30.6.2. Multiple Stresses: Synergies and Antagonisms

Sectoral approaches dominate ocean resource management, yet cumulative and interactive effects of individual stressors are known to be ubiquitous and substantial [*Halpern and Floeter*, 2008; *Halpern et al.*, 2008b]. Climate change consistently emerges as a dominant stressor in regional to global-scale assessments [*Halpern et al.*, 2008a; *Halpern et al.*, 2009b; *Selkoe et al.*, 2009], but land-based pollution, commercial fishing, invasive species, and commercial activities such as shipping all rank high in many places around the world, especially coastal waters [*Halpern et al.*, 2010; *Halpern et al.*, 2009b]. Such cumulative effects pose challenges to managing for the full suite of stressors to marine systems, but also present opportunities where mitigating a few key stressors can potentially dramatically improve overall ecosystem condition (e.g.[*Halpern et al.*, 2010]). The latter has often been seen as a potential strategy for reducing the rate of climate impacts on marine ecosystems by increasing ecosystem resilience, thus buying important time while the international community tackles greenhouse gas emissions [*Hoegh-Guldberg et al.*, 2007; *Hughes et al.*, 2003].

30.6.3. Economic Sectors

30.6.3.1.Fisheries

Many fisheries are fully exploited or overexploited [*Myers and Worm*, 2003; *Pauly et al.*, 1998]. Illegal, unreported and unregulated fishing; ineffective implementation of monitoring, control and surveillance; and overcapacity in fishing fleets are the three main impediments to sustainable harvest of world fisheries [*FAO*, 2010]. In developed countries, fish production and fisheries employment is decreasing, while the number of recreational fishers now exceeds professional ones in most industrialized countries [*Eide et al.*, 2011]. About 80% of production takes place in developing countries, employing increasingly more fishers (currently about 35 million ocean fishers). About 85% of the world's small-scale fishers are found in Asia [*FAO*, 2010]. Most of them harvest mixed species along the coast where there are also a large number unregistered subsistence fishers deriving food and income from aquatic resources. These communities are vulnerable in many ways, being poor and highly dependent on these local resources. On the other hand, some communities are highly mobile and are less vulnerable than dependents on single species or markets. Industrialized fisheries with large investments targeting specific species in other regions may be considered more resilient when it comes to technological and economic possibilities, but more vulnerable regarding the biological foundation of the fishery.

Based on evidence examined in the section 30.5 and elsewhere in this chapter, it is possible to make some broad generalizations regarding the growth or decline of major fisheries in a warming world (Fig 30-15). Drawing this information together, production of fisheries associated with the high latitude spring bloom systems are projected to increase, while almost every other ocean region is expected to have lower levels of fish production as climate change occurs. While these are general trends, they strongly suggest the fully understand the direction of these changes and how fisheries management should be modified in order to enable maximum sustainable production. Management decisions may have a greater impact on the economic conditions of the industrialized fisheries than climate change effects [*Eide*, 2007; *Vilhjálmsson et al.*, 2005]. Recent introduction of precautionary rules and ecosystem approaches to management in some countries gives guidelines for how to adapt to changes [*Garcia et al.*, 2003]. However, coastal small-scale fisheries in developing countries are in a different situation, where management tends to focus on infrastructure and economic growth rather than on adaptability.

[INSERT FIGURE 30-15 HERE

Fig 30-15: Expectations for major impacts of climate change on fishery catch potential by 2050, based on literature review in Chapter 30. Current and future fishery management status is not taken into account. Arrows indicate expectations in small regions. Climate change is expected to impact the ability of ecosystems to support fisheries in all major ocean regions. Predicting changes in fisheries catch is complicated by multiple effects of climate change on fish ecology and the confounding effects of changes in fishery management. However, we can generate some broad expectations about how climate change will impact the ability of ecosystems to support fisheries. Range shifts pole-wards of southern species and expanding ice free habitat may benefit fishery catch potential in high latitude regions, whereas, range shifts away from the equator may see declines in potential of tropical ecosystems to support fisheries (Cheung et al. 2010, Perry et al. 2010). Similarly, semi-enclosed seas may see losses in catch potential, due to geographic dead ends that hinder range shifts and increasing likelihood of anoxic zones (Cheung et al. 2010, Section 30.5.6). Loss of coral reef habitat in the tropics may also reduce fisheries catch potential. Recent observation and model predictions suggest declining primary production in subtropical gyres (Steinacher et al. 2010, Polovina et al. 2008), which may result in declines in fishery catch potential there, conversely, some models predict increases in Pacific tuna catch (Bell et al. 2011). Some of the world's most productive fisheries occur in Eastern Boundary systems. It is unclear whether climate change will cause increases or decreases in primary production and subsequently fisheries in these regions (Section 30.5.2). Deep sea ecosystems are extremely sensitive to rising temperatures and acidification (Section 30.5.7), so catch potential declines may be expected in these regions.]

30.6.3.2. Offshore Energy and Mineral Resource Extraction and Supply

The marine oil and gas industry is a key driver of energy and climate scenarios due to its role in supplying the liquid fossil fuels that are key contributors to greenhouse gas emissions. The industry also faces potential impacts from climate change on its ocean based activities. As operations move to waters 2,000m deep or more, far beyond continental shelves, the very large-scale moored developments are exposed to greater storm hazards and higher risks that are not well understood by existing climate/weather projections. Although there is a strong trend towards seafloor well completions with a complex of wells, manifolds and pipes that are not exposed to surface forcing, these systems face different hazards from instability of the unconsolidated sediments on which they rest [*Randolph et al.*, 2010]. Climate impacts on sea floor stability are widely debated due largely to uncertainties about the effects of methane and methane hydrates [*Archer et al.*, 2009; *Geresi et al.*, 2009; *Sultan et al.*, 2004]. The principle threat to oil and gas extraction in maritime settings is the impact of extreme weather on oil and gas extracting infrastructure [*Kessler et al.*, 2011], and this threat is likely to increase given that future storm systems are expected to have greater energy [*Emanuel*, 2005; *Knutson and Manabe*, 1998; *Knutson et al.*, 2010b; *Trenberth and Shea*, 2006]. Events such as Hurricane Katrina in 2005 have illustrated challenges likely to arise for this industry with projected increases in storm intensity [*Cashell et al.*, 2005; *Cruz and Krausmann*, 2008].

30.6.3.3. Shipping

International shipping accounts for > 80% of world trade by volume [*UNCTAD*, 2009a], but only ca. 3% of global CO_2 emissions from fuel combustion (IMO, 2009), although emissions are expected to increase two to three fold by 2050 [*UNCTAD*, 2009a]. Changing shipping routes [*Borgerson*, 2008], shifts in grain production and global markets, and new fuel and weather-monitoring technology may alter these emission patterns. Higher temperatures and extreme weather events, intensified by climate change, may interrupt ports and transport routes more frequently, damage infrastructure, and pose additional dangers to ship, crew and the environment [*UNCTAD*, 2009b].
Climate change may benefit maritime transport by reducing Arctic sea ice, shortening sailing distances between key ports [*Borgerson*, 2008] and thus decreasing total GHG emissions from ships. Currently, reliability of this route limits its use [*Schøyen and Bråthen*, 2011], and the potential full operation of the Northwest Passage and Northern Sea Route would require a transit management regime, regulation (e.g. navigation, environmental, safety and security) and a clear legal framework to address potential territorial claims that may arise, with a number of countries having direct interests in the Arctic.

30.6.3.4.Tourism

Tourism is one of the world's largest industries. It is affected by climate change, global economic and socio-political conditions, and their interactions. Climate change affects the attractiveness of destinations directly through an influence on temperature, precipitation, extreme events, and sea level rise, and indirectly through species biodiversity and composition [*UNWTO and UNEP*, 2008]. Impacts of climate change on charismatic ecosystems such as coral reefs are likely to change the flow of tourists to many markets. Preferred tourism conditions are projected to shift towards higher latitudes with climate change, or from summer to cooler seasons [*Amelung et al.*, 2007]. This is likely to impact business success and strategy. For example, whale watching businesses ($1 billion worldwide in 2001) will be affected by climate change impacts on whale distributions, abundance, and species composition [*Lambert et al.*, 2010]. Anticipated changes include a decline of deep-water whale species diversity in the tropics and increases at higher latitudes [*Whitehead et al.*, 2008].

30.6.4. Natural Ecosystems and Services

Human welfare depends on a wide range of ecosystem services that are generated by the world's oceans. Many of these services are provided by coastal and shelf areas, and are consequently addressed in other chapters. Oceans contribute provisioning services such food (see 30.6.3.1: Fisheries above), regulating (e.g. gas exchange, climate regulation) and supporting (e.g. nutrient recycling, primary production) services [*Millennium Ecosystem Assessment*, 2005]. The latter service categories are critically important and tend to transcend immediate demands placed on provisioning services. The accumulating evidence that fundamental processes within the ocean are shifting rapidly should be of major concern, especially with respect to the ability of regulating and supporting ecosystem services to underpin current and future human population demands [*Rockstrom et al.*, 2009]. Protecting large sections of open ocean from human exploitation is increasingly being proposed and implemented to protect and maintain ocean ecosystems and function [*Agardy et al.*, 2011; *Edgar*, 2011; *Game et al.*, 2009]. The planetary scale changes that are currently occurring, however, require concerted international action on the fundamental drivers of change (anthropogenic greenhouse gas emissions).

30.6.5. Health and Social Security

30.6.5.1.Disease, Harmful Algae Blooms, and Seafood Security

Changing patterns of disease, water and food insecurity, vulnerable shelter and human settlements, extreme climatic events, and population growth and migration are the major threats to public health related to climate change [*Costello et al.*, 2009]. Effects directly or indirectly related with basin-scale changes in the ocean (e.g. temperature, rainfall, plankton populations) [*McMichael et al.*, 2006] include spread of pathological diseases, seafood diseases, biological invasion and ballast-water discharge. Climate change impacts on ocean climates may influence the distribution of vector-borne diseases like cholera, malaria and salmonella. Cholera outbreaks induced by *Vibrio cholerae* and other enteric pathogens might increase with plankton blooms (e.g. marine algae and copepods) correlated with multi-decadal fluctuations of ENSO [*Colwell*, 1996; *Pascual et al.*, 2000; *Patz et al.*, 2005; *Rodo et al.*, 2002]. The predominately negative impacts are likely to be more serious in low-income countries, for example southeast Asia, southern and east Africa, and various regions of South America [*Patz et al.*, 2005], which suffer from inefficient and under-resourced health systems [*Costello et al.*, 2009].

30.6.5.2.Social Security and Oceanic Fisheries

Impacts of climate change on open-ocean fish populations (especially the high seas) are expected to affect the economics of fishing and the social security of fishing nations because of changes in the price and value of catches, fishing costs, income to fishers and fishing companies, national labour markets, and industry re-organisation [*Sumaila et al.*, 2011]. A study of the potential vulnerabilities of national economies to the effects of climate change (based on air temperature changes projected by the IPCC A1F1 and B2 scenarios) on fisheries concluded that

Malawi, Guinea, Senegal, Peru, Columbia, Bangladesh, Cambodia, Pakistan, and Yemen are most vulnerable [*Allison et al.*, 2009]. In contrast, countries at high latitudes are likely to experience increases in their potential fisheries catch [*Cheung et al.*, 2010]. Tuna fisheries have high climate change sensitivity. In the western equatorial Pacific, nations with the greatest dependence on tuna fisheries (e.g. Kiribati, Nauru, Tuvalu, Tokelau) are likely to benefit as tuna distributions shift eastward with warmer climates [30.5.1]. In contrast, climate-mediated reductions of tuna in the western Pacific are expected to have limited economic impacts because these fisheries currently provide only modest contributions to the GDP of nations in this region [*Bell et al.*, 2011].

30.6.6. Multi-Sector Synthesis and Key Vulnerabilities

The pervasive and interconnected nature of the ocean touches on almost all aspects of life on Earth. As a result, it is impossible to assess the impacts of climate change on the open ocean as a series of isolated regions and sectors. Understanding the changes that are occurring within the world's oceans is still limited, as is our ability to predict how future changes will affect this vital part of the earth system. It is clear, however, that high levels of change that are projected for key variables such as temperature, pH and carbonate chemistry (Table 30-4, Figure 30-6) suggest fundamental changes in ocean ecosystem structure and function are almost certain. Given our high dependence on ocean ecosystem services, these changes are likely to escalate the risk of poverty, food insecurity, and social dysfunction along many coastlines of the world. At the same time, industries such as fishing and shipping will face increasingly uncertain conditions within the ocean, which may offer opportunities as well as significant challenges. The impacts, connections and opportunities are explored in Figures 30-15 and 30-16.

30.6.7. Global Frameworks for Decisionmaking

The world's oceans represent a vast resource that drive the environmental conditions and ultimately determine life on Earth. From the analysis presented here, the open ocean is changing fundamentally as result of the activities of humans at the local and global scales (very high confidence). We are only just beginning to understand both the scale and complexity of these changes, highlighting the critical importance of rapidly reducing the emissions of greenhouse gases while at the same time seeking strategies to reduce the impact of changing circumstances and ecosystems across the planet. In the latter case, strong frameworks for global decision-making are critical for devising and implementing adaptation strategies for reducing the impacts of rising greenhouse gases such as CO_2.

Adaptation strategies that reduce the impact of climate change on ocean ecosystems and their services include managing local factors not related to climate change. Overfishing, pollution, deteriorating water quality, and habitat loss often interact with climate change to produce greater effects than if each were to occur on their own (i.e. synergistic interactions). Coral reefs, for example, will recover three times faster from mass coral bleaching and mortality if healthy populations of herbivorous fish are maintained [*Hughes et al.*, 2003], indicating that controlling overfishing will help maintain coral-dominated reef systems while the international community reduces the emissions of greenhouse gases and stabilises global temperature. In contrast, where interactions between climate change and local factors are acting in opposition (i.e. antagonistic interactions that ‘cancel out’ individual influences), deploying strategies that target antagonistic local factors could manage broader climate change impacts. Understanding the nature and direction of interactions will play a key role in establishing adaptation strategies and frameworks.

Many nations 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 important in terms of assisting nations in developing local adaptation solutions to their ocean resources. By sharing common experiences and strategies through global networks, nations have the chance to tap into a vast array of options with respect to responding to the impacts of climate change on the global resources.

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

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

30.7.1. Major Conclusions

There is overwhelming evidence that the physical, chemical and biological conditions within the open oceans are changing rapidly. Many of these changes are large-scale, interconnected, and have no recent analogue in thousands if not millions of years, and involve changes to the physiological behaviour of organisms as well as ecosystem processes such as primary productivity, marine calcification and gas exchange. As a result, marine organisms and ecosystems are undergoing fundamental changes. Our understanding of how climate change has been affecting the world oceans, however, has been limited by the difficulty of accessing marine environments and the relatively small number of studies that have tackled this otherwise-important area. These studies have also been challenged by variability that operates on a variety of spatial and temporal scales, and which can amplify the impacts of ocean warming and acidification.

While each of the seven ocean regions examined here exhibit different patterns of change, there are several responses from marine ecosystems that are being seen across all ocean regions. A comprehensive analysis of recent literature for example, reveals that 84% of recent changes reported in the peer-reviewed scientific literature are highly consistent with changes expected under climate change. Organisms are rapidly moving to higher latitudes with ‘mobile’ organisms (phytoplankton, zooplankton and fish) moving at the most rapid rates (Figure 30-16A). At the same time, seasonal triggers for life history events are advancing by 2-5 days.decade^{-1}. These changes approach and exceed in many cases those seen for terrestrial organisms and ecosystems. These fundamental changes suggest increasing asynchrony between organisms and their competitors and food, as well as the increasing likelihood of ecosystem assemblages that have no recent analogue.

[INSERT FIGURE 30-16 HERE
Figure 30-16: Summary of regional impacts (and opportunities) of climate change on the world’s open oceans.]

High latitude spring bloom systems are critically important to 36% of the world's fisheries. Fundamental changes as result of ocean warming and acidification are occurring in the composition of plankton communities which are driving changes to the species composition and abundance of key fisheries (Figure 30-16 A,B). Ecological regime shifts have occurred with substantial impacts on key fisheries and dependent industries, and are likely to continue as warming continues. Climate change may lead to greater productivity in some fisheries through warmer temperatures, increased upwelling and reduced sea ice.

Many ocean regions (e.g. Semi-Enclosed Seas, Eastern Boundary Currents, Equatorial Upwelling Regions, and Subtropical Gyres) are experiencing changes in the extent to which upper ocean waters mix with deeper layers

(Figure 30-16C). These changes affect the supply of nutrients to the surface waters in the ocean, and have important ramifications for the primary production of ocean ecosystems as well oxygen concentrations in many parts of the ocean. In several of the world's semi-enclosed oceans (Baltic, Black, and Mediterranean Seas), ocean warming is leading to greater water column stability, which in turn has reduced mixing and primary productivity, leading to increased hypoxia at depth. In the Eastern Boundary Current regions, however, increasing wind strength may be driving increased upwelling and consequently greater levels of primary productivity. In the latter case, however, higher levels of primary productivity and a subsequently higher flux of organic carbon into the deep ocean is resulting in reduced oxygen levels at depth.

Increasing sea temperatures are also driving mass coral bleaching and mortality, as well as heat-stress events in shallow, semi-enclosed waters such as the Mediterranean Sea. These events have increased in intensity and frequency over the past several decades. Further increases in sea temperature are likely to continue this trend, with the future of many ecosystems such as coral-dominated reefs being in doubt as ocean temperatures increase (Figure 30-16 D,E). The impacts of losing these highly productive and biologically diverse ecosystems is likely to impact hundreds of millions of people that live in close association with the world's coastal areas.

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

30.7.2. Emerging Themes

Rapid change in the world’s oceans is an emerging theme within our understanding of climate change. Until recently, the impacts of climate change on the ocean were thought to be less than that on land due to the high thermal capacity of water. However, it is clear from this analysis that climate change may be having greater and more rapid impacts on ocean ecosystems (Figure 30-16). The detection and attribution analysis undertaken here [*Poloczanska et al*., 2012] reveals some of the most rapid rates of change in the distribution and abundance of organisms in response to climate change have occurred in the world’s oceans.

Dissolved oxygen concentrations are declining across vast regions of the ocean. The decrease in oxygen is a consequence of warming and stratification of the water column in some areas, changes in local weather patterns in others, and temperature influences on the ratio of rate of metabolism. The decline in oxygen concentrations in large parts of the ocean is of great concern given the potential impacts that spreading hypoxia could have for marine species and ecosystems. In this respect, projected warming of sea temperature under the current business as usual scenario are likely to rapidly enhance water column stratification, bacterial metabolism and consequently drive major expansion in deep-ocean areas that are currently low in oxygen. Based on the impact so far from 0.8°C increase in average global temperature, these future changes are likely to have transformative impacts on important ocean ecosystems and fisheries throughout the world.

Changes to water column mixing and ventilation have driven changes to productivity and other aspects such as oxygen concentration in a number of key areas of the world's oceans. While there is considerable discussion about how climate change will affect upwelling systems, there is concern that changes to the land-ocean temperatures may increase upwelling in some areas and a decrease in others (Figure 30-16F). At present, there is little information and understanding about the response of these important areas of fisheries production in the rapidly warming world. This must be a priority of future research given the implications for global food security.

The impacts of ocean acidification on marine organisms and ecosystems (Figure 30-16G) has emerged as a major concern especially given the robust evidence that the current chemistry of the ocean is outside where it has been for at least 1 million years. At current rates of increase atmospheric CO_2, the acidity of the ocean will surpass any seen over the last 40 million years [*Hoegh-Guldberg et al*., 2007; *Raven et al*., 2005]. The growing literature from the past five years has increasingly documented a major array of changes from the reduced calcification of coral reefs and pteropods, to impacts on animal reproduction, navigation, and olfaction. Ocean acidification is rapidly emerging as a very serious yet uncharted risk for all ocean regions, although the greatest impacts of changing pH and carbonate ion concentrations are being felt at higher latitudes due to the colder temperatures and hence greater flux of CO_2 entering these waters.

Changes to the physical and chemical nature of ocean waters are also driving changes in the distribution and abundance of primary production (Figure 30-16H). These changes are beginning to have fundamental and large-scale influences on the distribution and abundance of primary productivity, which has implications for both fisheries as well as the flux of organic carbon into the deep ocean. While the current decreases in productivity that have been reported in the major ocean basins need to be considered in the light of natural climate cycles such as ENSO and PDO, it is important that we develop a greater understanding of the potential implications of these rapid changes in ocean productivity. In this respect, a major erosion of ocean services from provisioning to regulating may be underway if ocean productivity continues to decrease over and above the background variability within the ocean climate systems. Extending these changes over the coming decades and century would be the basis for serious global concern. In combination with changes to sea temperature, changes to the distribution of ocean productivity has serious implications for the productive pelagic fisheries that many countries depend on (Figure 30-15 and 30-16I). Understanding these current changes should be an urgent priority of the international community.

Responses of biological systems to changes in ocean temperature, chemistry and circulation often amount to the reorganization of biological assemblages. Warm-water species are moving into historically cooler areas, while some cool-water species remain. In addition, the physiological performance of species is varying as the physical environment changes, which flow on to alter ecosystem function and processes. Change in the diversity and composition of species and their interactions often has important consequences for ecosystem function and services. For example, biological diversity can enhance fisheries productivity and stability [*Schindler et al*., 2010; *Worm et al*., 2006], and changes in key species can have cascading effects on ecosystem structure and function. These types of novel and unprecedented changes present enormous challenges in terms of implementing the sustainable use of ocean resources such as fisheries.

30.7.3. Research and Data Gaps

Despite the fact that Earth is dominated by the ocean, we are only beginning to understand the physical, chemical and biological processes that underpin its ability to provide a range of ecosystem and planetary services. This situation has arisen because of the relative difficulty of accessing ocean environments, meaning that serious measurements have only been underway for the past 60 years. Given the importance of the world's oceans, it is an imperative that we increase our understanding of how climate change and ocean acidification are likely to influence the structure and function of ocean systems.

Major gaps exist in our understanding of how key physical processes such as upwelling are likely to respond to conditions on a warming planet. These areas provide an enormous amount of the protein from fisheries that are driven by the mixing of deep, nutrient-rich waters into the photic zone. At the same time, understanding the current changes that are occurring within the subtropical gyre systems of the world's major oceans is also important. Resolving how these systems are likely to respond to climate change, especially in the light of strong background influence of short to long-term natural climate cycles such as ENSO and PDO, should be a priority of future research. The deep ocean below 1000 m is the ecosystem about which we know the least. In this respect, ramping up our understanding of deep-ocean habitats and how these may be changing under the influence of both climate change and non-climate change factors is of great importance.

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

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

30.8. Case Studies

30.8.1. Upwelling Intensification, Stratification-Ventilation, and Primary Productivity

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

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

[INSERT FIGURE 30-17 HERE
Figure 30-17: Diagrammatic representation of the interaction between land sea temperature, wind direction and strength, and coastal upwelling.]

30.8.2. The Detection and Attribution of Regional Climate Change Impacts on Coral Reefs: What does the Future Hold?

The impacts of ocean warming on coral reef ecosystems (Box 29-1) have led to the development of detection algorithms that can reliably predict the spatial and temporal patterns of thermal stress related coral bleaching and mortality based on Sea Surface Temperature (SST) anomalies [*Eakin et al.*, 2010; *Strong et al.*, 2011]. The accumulated evidence provides a strong attribution and traceable linkages between major impacts on coral reef ecosystems (mass coral bleaching and mortality) and increasing global temperatures (high confidence). This 'attribution chain' also enables projections of how the frequency and intensity of mass coral bleaching is likely to change as global temperatures increase [*Donner*, 2009; *Donner et al.*, 2005; *Hoegh-Guldberg*, 1999]. Using low (RCP 2.6), moderate (RCP4.5), high (RCP 6.0), and very high (RCP 8.5) greenhouse gas scenarios (CMIP5), the projected changes in the frequency of mass coral bleaching and mass coral mortalities for this century were calculated using thresholds currently in use to detect impacts from satellites with a high degree of accuracy [*Eakin et al.*, 2010; *Strong et al.*, 2011]. In this respect, coral populations that experience sea temperatures of 1°C above the long-term summer maximum for a month or more (i.e. 1 Degree Heating Month, or DHM) will experience bleaching (WGII Ch6). If temperatures are hotter for longer, most corals within a community (> 90%) will bleach and the incidence of disease and mortality will increase [*Hoegh-Guldberg*, 1999]. In the most comprehensive study to date, *Eakin et al.* [2010] revealed that coral communities in the Caribbean in 2005 experienced near-100% bleaching and mortality rates of 30-40% (up to 70-80%) when DHM values reached 4 or more. Using this information, it is possible to project how rising sea temperatures will impact coral communities in the future under different climate scenarios.

This methodology was used to examine how the incidence of mass coral bleaching and mortality events are likely to vary over the coming decades and century for 4 major coral reef realms (Southeast Asia/Coral Triangle, Western Pacific, Caribbean and Western Indian Ocean) under the various scenarios (Table 30-4, Figure 30-18). The results of these projections are remarkably similar between the 4 regions and are likely to hold for the coral reefs globally[*Donner et al.*, 2005; *Hoegh-Guldberg*, 1999]. Under all 4 scenarios, coral bleaching (DHM $\geq$ 1) events occur every 1-2 years by 2030-2050, with the Caribbean showing the most rapid rise, having an annual occurrence of mass bleaching and conditions by 2030 (Figure 30-18A). The incidence of mass mortalities (DHM $\geq$ 5) shows a distinct difference between 4 scenarios (Figure 30-18B). Under BAU (RCP 8.5), mass mortality events occur every 1-2 years by 2060. Only under the lowest scenario (RCP 2.5) do ocean temperatures in all but one region (Caribbean) stabilise and mass mortality events remain below a 1-in-10 year occurrence (Figure 30-18B.). Given that coral communities take at least 10 years to recover from mass mortality events [*Graham et al.*, 2011], frequencies of annual mortality events above 10% severely increase the risk that of coral-dominated populations within the four major coral reef regions will be lost. This analysis supports similar conclusions of previous studies [*Done et al.*, 2003; *Donner et al.*, 2005; *Hoegh-Guldberg*, 1999].

[INSERT FIGURE 30-18 HERE
Figure 30-18: Average yearly percentage of occurrence of DHM ≥ 1 (representative of coral bleaching events) and DHM ≥ 5 (representative of mass coral mortality events) for the period 1980-2099 (with climatology and DHMs derived from HadISST 1.1 for 1880-2009; and for 2010-2099 the climatology was derived from CMiP-5 historic runs and modelled RCP 2.6, 4.5, 6.0 & 8.5 values were used to derive DHMs) in each of the four coral regions (Figure 30-1, Table 30-1). Degree Heating Months (DHM) can then be calculated by adding up the anomalies using a 4-month rolling sum (after Donner et al., 2007). A value of 50% means that the event is occurring once every two years on average, a value of 100% means that the event is occurring every year.]

30.8.3. Regional Fisheries under Global Climate Change

During the second half of the 20th century, and particularly during the 1960s and 1970s, the industrialization of fisheries increased the world's fish catches at rates higher than ever recorded. In many regions, the catches increased beyond sustainable harvest before resulting in declines in stock abundance and catches since the 1980s. On a global scale, wild fish catches displayed a more gradual increase during the same period but have leveled out at about 90 million tons from the early 1990s. However, due to aquaculture production the total harvest from the sea has continued to increase, also from the 1990s. Presently, aquaculture production has passed 50 million tons (FAO 2010).

The oceans' productivity, from primary production to harvestable resources, varies substantially between regional ecosystems. As for terrestrial ecosystems, there are oceanic "rainforests" and "deserts". The highly-productive regions are particularly found in near-coastal ecosystems and in the northern boreal marine ecosystem (Figure 30-1,

Figure 30-19). The four ecosystem provinces, high-latitude spring bloom systems, western boundary systems, eastern boundary systems and semi-enclosed seas comprise only 19.5% of the surface of the world's ocean, but provide 80% of the world oceans fish catches.

[INSERT FIGURE 30-19 HERE
Figure 30-19: Fish catches and areas for ecosystem regions shown in Figure 30-1. Red columns: average fish catch (millions tons yr^{-1}) for the period 1970-2006. Blue columns: area (millions km^2).]

On the oceanic scale there is high correlation between fish catches and primary production. However, each of the oceans contains a number of specific ecosystems, with different structures and functions where regions with the highest primary productivity also have highest fish catches. Climate change will impact the world's fishes directly by the changing temperature and indirectly by altering the primary production and the structure and functions of the ecosystems. Such changes cause changes of species diversity, competition, recruitment, growth and distribution [*Moloney et al.*, 2011]. The close relationships between primary productivity and fish catches demonstrate that projections of the world's primary production are of particular interest for assessing the changes in the *productivity* of the world fisheries, but the major production occurs in selected regions. However, changes in *species diversity* are important in low-productive provinces.

Coupled global carbon cycle-climate models show a decrease in marine primary productivity through the 21th century [*Steinacher et al.*, 2010], although with large regional differences. The future climate change could amplify the geographical differences in fish production with low-production regions becoming less productive and high-production regions become more productive.

In addition to the impact from changes in production of food for the fish, fish populations will also change their spatial distributions by geographical shifts in the thermal environment to which the various species are adapted resulting in pole-ward displacement of species [*Cheung et al.*, 2009] with species invasions at higher latitudes and extinctions primarily in tropical waters and in polar regions. This will ultimately result in a 30 -70% increase in fish catch potential at higher latitudes by the mid 21st century and a decrease by 40% in the tropics [*Cheung et al.*, 2010]. Species extinctions will generally occur at lower rates in oceanic than terrestrial environments. Human societies in tropical waters will be most vulnerable to changes in ocean fish production [*Perry*, 2011].

Frequently Asked Questions

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

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

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

It is impossible to prevent exposure of natural systems to climate change, but we can manage the combined impacts of climate and other human activities such as land use, pollution, eutrophication, habitat destruction, invasive species and fishing. These activities combine in different ways with climate change, with some acting in opposition (antagonistic) while others act together to produce an enhanced effect (synergistic). Where we find synergistic interactions, we can devote our management efforts to reducing the non-climate activities thus minimizing degradation of natural systems. For example, maintaining coastal water quality will partially alleviate the impact of thermal stress on sea grass beds. Identifying the type of interactions between climate and human activities will be crucial for managing climate change impacts on natural systems.

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

Even small amounts of warming will lead to major changes in natural systems. Despite less warming in equatorial regions than elsewhere, many tropical species are under threat from future warming as they are already near their upper thermal tolerance limits. Similarly, despite slower warming over ocean than land, bands of equal temperature (isotherms) are migrating polewards at similar or faster rates in the ocean implying that marine species will have to move at rates comparable to, or faster than, land species to track thermal environments. Rates of change in seasonal temperature peaks are also similar over ocean and land, implying comparable shifts in timing of life history events such as earlier reproduction in spring. Therefore, even the slower warming in the tropics and in the oceans will pose challenges to species and reorganize natural systems.

FAQ 30.4: How will marine primary productivity change?

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

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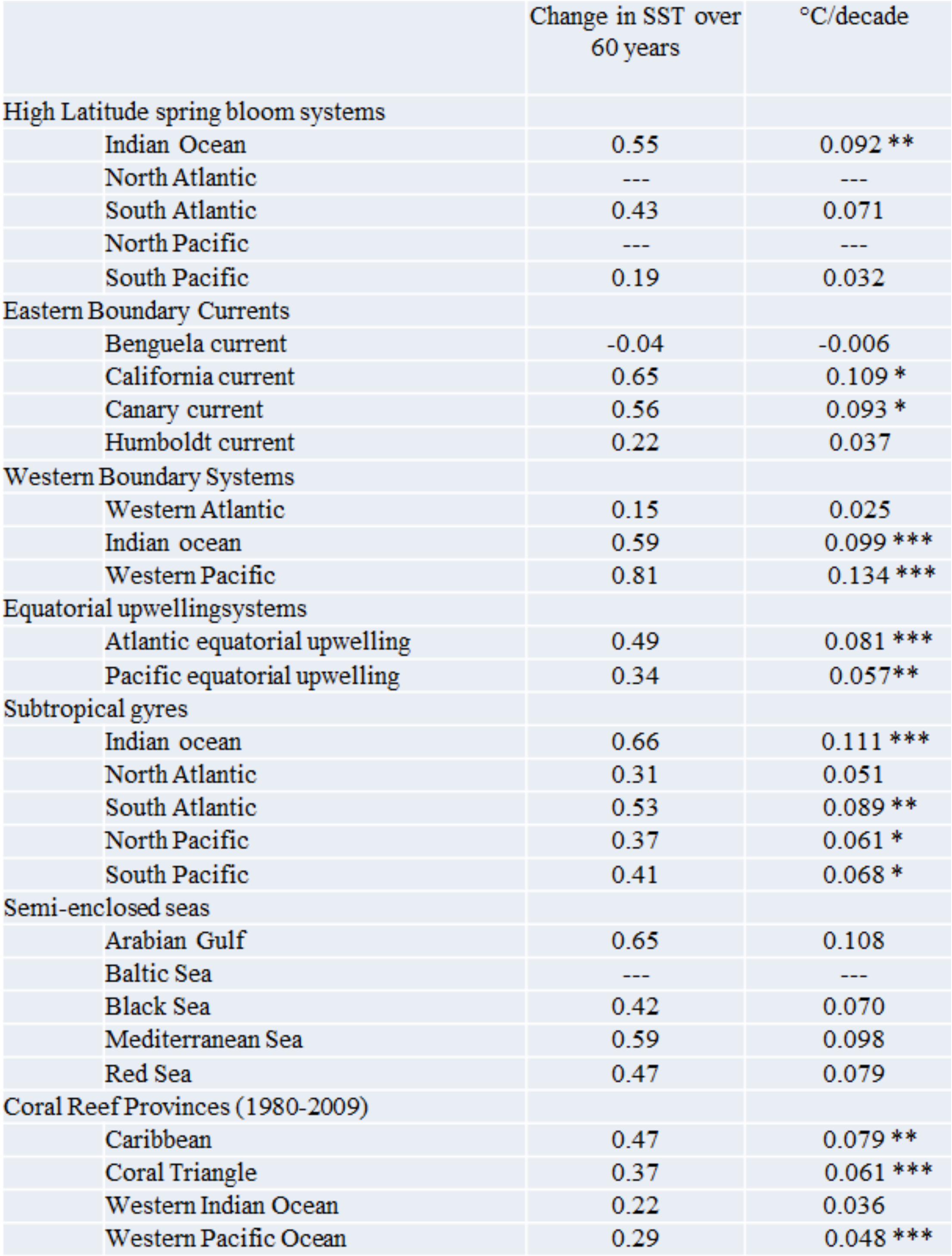
Table 30-1: Area, average primary, and fishery productivities for the seven regions.

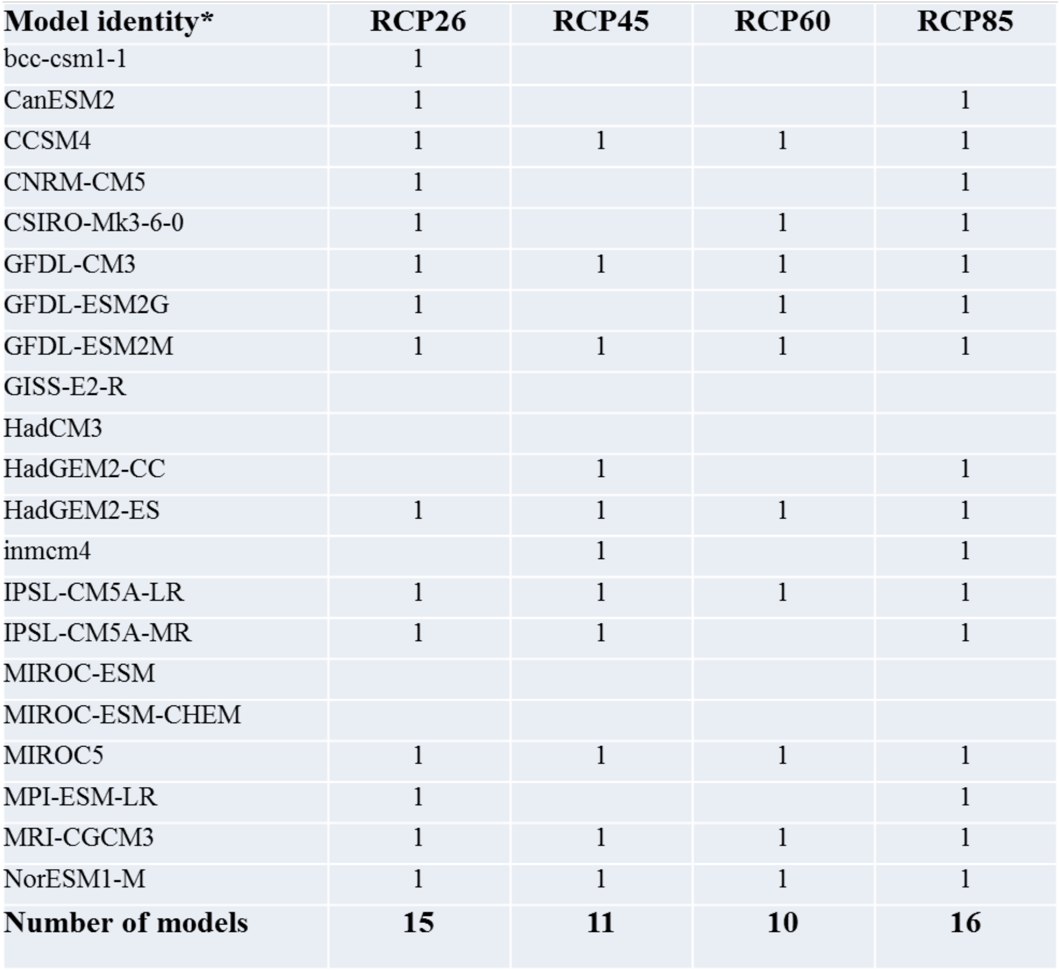
Area		Description	Area (%)	Primary Productivity (%)	Fisheries Productivity (%)
1. High Latitude Spring Bloom Systems (HLSBS)	Northern Section	From 35oN and 35oS to the edge of the winter ice). Strong seasonal cycle of primary productivity that is nutrient limited at times and which becomes more pronounced towards higher latitudes where primary production shifts to a single peak during early spring and decreases to near zero in winter (numbered references).	10.6	22.6	29.6
	Southern Section		14.4	20.4	6.8
2. Equatorial upwelling systems (EUS)		Consist of highly productive regions along eastern edge of the Pacific and Atlantic oceans.	8.2	9.0	5
3. Semi-enclosed seas (SES)		Defined here as large landlocked seas (>200,000 km2) with single narrow passageways (<120 km). Includes Arabian Gulf, Red, Mediterranean, Black, and Baltic seas.	1.1	2.3	3.3
4. Western Boundary Systems (WBS)		Include diverse marine ecosystems that are influenced by different location-specific oceanographic processes and primary productivity values. Like the EBS, light is abundant although nutrients may be restricted spatially and temporally by a number of different factors (e.g. stratification, coastal run-off).	6.2	10.6	28
5. Eastern Boundary Currents (EBC)		Consist of four major components; the Canary Current and Benguela Current in the Atlantic Ocean, and the California Current and the Humboldt Current in the Pacific Ocean. In contrast to the high latitude spring-bloom systems, large levels of primary production tends to occur continuously, driven by regional wind systems that drive the upwelling of nutrients from the deep to surface.	1.7	7.0	20
6. Subtropical gyres (STG)		Found in all three oceans and exhibit low productivity due to warm and highly stratified water columns which restricts nutrient supply to euphotic layer ("ocean nutrient deserts).	41.0	22.0	8
7. Deep Ocean (DO)		Defined here as habitats below 1000m representing the largest habitat on Earth. Despite its large size, our understanding of the deep ocean is minimal. Interacts strongly with the upper ocean through the sedimentation of biogenic material, remineralisation, vertical mixing, upwelling, downwelling and vertical migrations (including ontogenetic).	88.0	0	0.5

Table 30-2: Net changes in Sea Surface Temperature (and rate of change) for the period 1950-2009 for key components of the six ocean regions explored in this chapter. Data were obtained from the Hadley Centre (HadISST 1.1). Also shown are data for 4 key coral reef regions. Statistical significance (Simple linear regression) is indicated (*** p< 0.001; ** p< 0.01 * p< 0.05) – the rest are not significantly different from zero. Missing values indicated by '---' due to artifacts and arising from intermittent sea ice (NB reader: to be resolved by next draft; SOD).



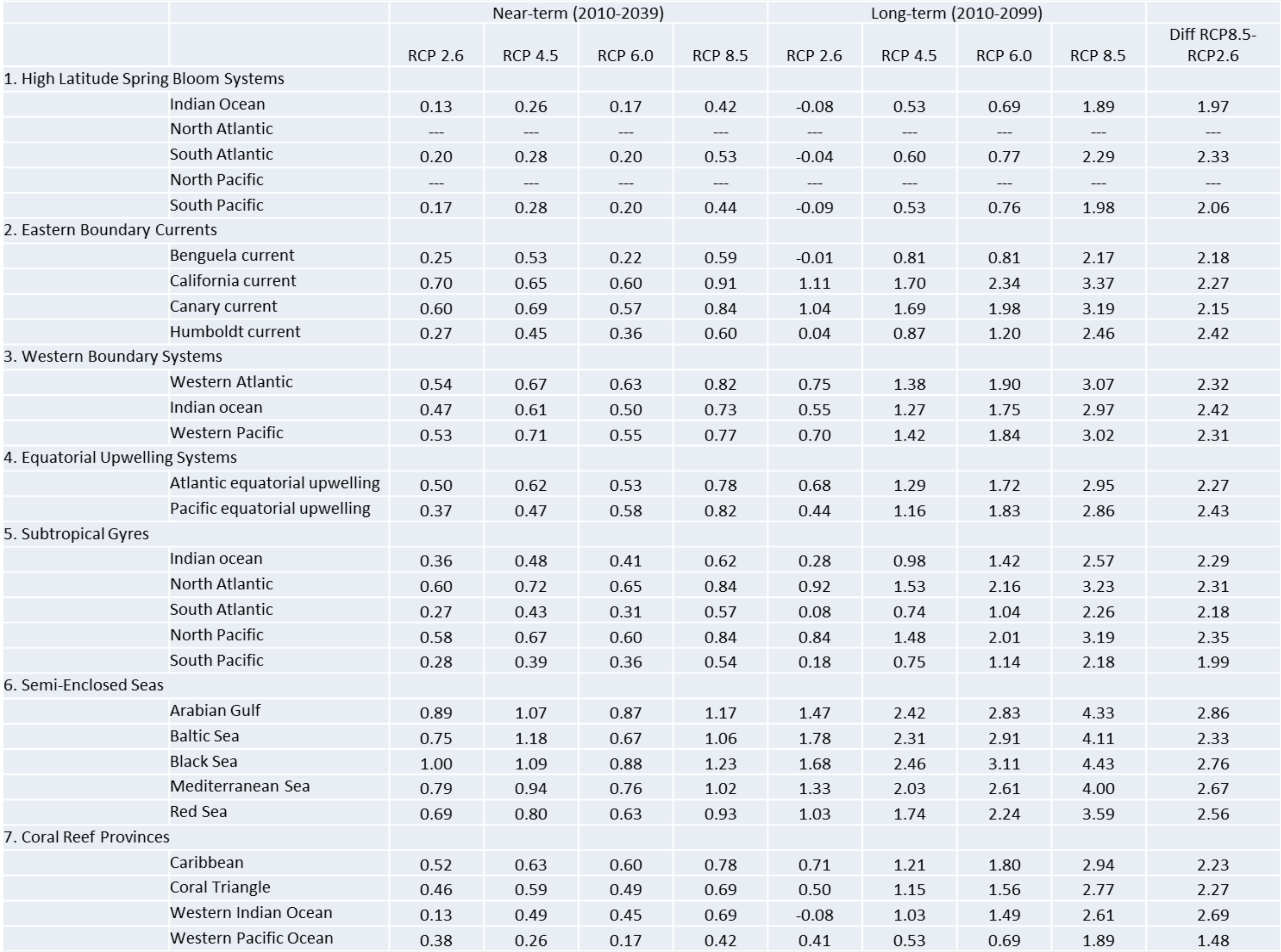
		Change in SST over 60 years	°C/decade
High Latitude spring bloom systems			
	Indian Ocean	0.55	0.092 **
	North Atlantic	---	---
	South Atlantic	0.43	0.071
	North Pacific	---	---
	South Pacific	0.19	0.032
Eastern Boundary Currents			
	Benguela current	-0.04	-0.006
	California current	0.65	0.109 *
	Canary current	0.56	0.093 *
	Humboldt current	0.22	0.037
Western Boundary Systems			
	Western Atlantic	0.15	0.025
	Indian ocean	0.59	0.099 ***
	Western Pacific	0.81	0.134 ***
Equatorial upwellingsystems			
	Atlantic equatorial upwelling	0.49	0.081 ***
	Pacific equatorial upwelling	0.34	0.057**
Subtropical gyres			
	Indian ocean	0.66	0.111 ***
	North Atlantic	0.31	0.051
	South Atlantic	0.53	0.089 **
	North Pacific	0.37	0.061 *
	South Pacific	0.41	0.068 *
Semi-enclosed seas			
	Arabian Gulf	0.65	0.108
	Baltic Sea	---	---
	Black Sea	0.42	0.070
	Mediterranean Sea	0.59	0.098
	Red Sea	0.47	0.079
Coral Reef Provinces (1980-2009)			
	Caribbean	0.47	0.079 **
	Coral Triangle	0.37	0.061 ***
	Western Indian Ocean	0.22	0.036
	Western Pacific Ocean	0.29	0.048 ***

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



Model identity*	**RCP26**	**RCP45**	**RCP60**	**RCP85**
bcc-csm1-1	1			
CanESM2	1			1
CCSM4	1	1	1	1
CNRM-CM5	1			1
CSIRO-Mk3-6-0	1		1	1
GFDL-CM3	1	1	1	1
GFDL-ESM2G	1		1	1
GFDL-ESM2M	1	1	1	1
GISS-E2-R				
HadCM3				
HadGEM2-CC		1		1
HadGEM2-ES	1	1	1	1
inmcm4		1		1
IPSL-CM5A-LR	1	1	1	1
IPSL-CM5A-MR	1	1		1
MIROC-ESM				
MIROC-ESM-CHEM				
MIROC5	1	1	1	1
MPI-ESM-LR	1			1
MRI-CGCM3	1	1	1	1
NorESM1-M	1	1	1	1
Number of models	**15**	**11**	**10**	**16**

Table 30-4: Average absolute change in SST (ºC) for each of the four CMIP-5 Representative Concentration Pathways (RCP). Rates of change were estimated in each 30-year period by fitting a linear regression to each grid cell within each region (Figure 30-1, Table 30-1) and then averaging the results across all grid cells in the region. The net change in Sea Surface Temperature (SST) was calculated by multiplying rates of change by 30 years. The total change from 2010-2099 was calculated by adding the net changes in the three successive 30-year periods up to 2099.



		Near-term (2010-2039)				Long-term (2010-2099)				
		RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5	Diff RCP8.5-RCP2.6
1. High Latitude Spring Bloom Systems										
	Indian Ocean	0.13	0.26	0.17	0.42	-0.08	0.53	0.69	1.89	1.97
	North Atlantic	---	---	---	---	---	---	---	---	---
	South Atlantic	0.20	0.28	0.20	0.53	-0.04	0.60	0.77	2.29	2.33
	North Pacific	---	---	---	---	---	---	---	---	---
	South Pacific	0.17	0.28	0.20	0.44	-0.09	0.53	0.76	1.98	2.06
2. Eastern Boundary Currents										
	Benguela current	0.25	0.53	0.22	0.59	-0.01	0.81	0.81	2.17	2.18
	California current	0.70	0.65	0.60	0.91	1.11	1.70	2.34	3.37	2.27
	Canary current	0.60	0.69	0.57	0.84	1.04	1.69	1.98	3.19	2.15
	Humboldt current	0.27	0.45	0.36	0.60	0.04	0.87	1.20	2.46	2.42
3. Western Boundary Systems										
	Western Atlantic	0.54	0.67	0.63	0.82	0.75	1.38	1.90	3.07	2.32
	Indian ocean	0.47	0.61	0.50	0.73	0.55	1.27	1.75	2.97	2.42
	Western Pacific	0.53	0.71	0.55	0.77	0.70	1.42	1.84	3.02	2.31
4. Equatorial Upwelling Systems										
	Atlantic equatorial upwelling	0.50	0.62	0.53	0.78	0.68	1.29	1.72	2.95	2.27
	Pacific equatorial upwelling	0.37	0.47	0.58	0.82	0.44	1.16	1.83	2.86	2.43
5. Subtropical Gyres										
	Indian ocean	0.36	0.48	0.41	0.62	0.28	0.98	1.42	2.57	2.29
	North Atlantic	0.60	0.72	0.65	0.84	0.92	1.53	2.16	3.23	2.31
	South Atlantic	0.27	0.43	0.31	0.57	0.08	0.74	1.04	2.26	2.18
	North Pacific	0.58	0.67	0.60	0.84	0.84	1.48	2.01	3.19	2.35
	South Pacific	0.28	0.39	0.36	0.54	0.18	0.75	1.14	2.18	1.99
6. Semi-Enclosed Seas										
	Arabian Gulf	0.89	1.07	0.87	1.17	1.47	2.42	2.83	4.33	2.86
	Baltic Sea	0.75	1.18	0.67	1.06	1.78	2.31	2.91	4.11	2.33
	Black Sea	1.00	1.09	0.88	1.23	1.68	2.46	3.11	4.43	2.76
	Mediterranean Sea	0.79	0.94	0.76	1.02	1.33	2.03	2.61	4.00	2.67
	Red Sea	0.69	0.80	0.63	0.93	1.03	1.74	2.24	3.59	2.56
7. Coral Reef Provinces										
	Caribbean	0.52	0.63	0.60	0.78	0.71	1.21	1.80	2.94	2.23
	Coral Triangle	0.46	0.59	0.49	0.69	0.50	1.15	1.56	2.77	2.27
	Western Indian Ocean	0.13	0.49	0.45	0.69	-0.08	1.03	1.49	2.61	2.69
	Western Pacific Ocean	0.38	0.26	0.17	0.42	0.41	0.53	0.69	1.89	1.48

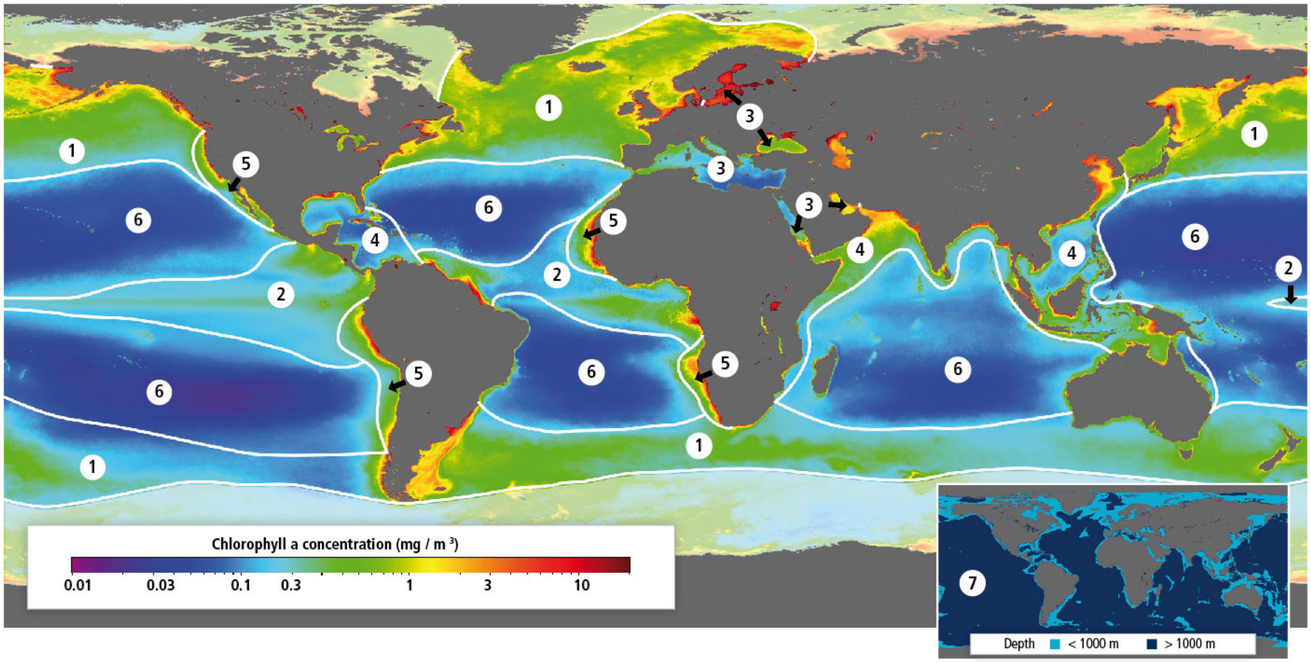


Figure 30-1: The world's non-polar oceans have been separated into seven major regions, with polar oceans being excluded due to treatment elsewhere (Ch28). The chlorophyll concentration averaged over the period from Sep 1997 – 30 Nov 2010 (NASA) is also shown. Together with key oceanographic features, primary production was the basis for separating the ocean into the regions shown. The map insert shows the distribution of Deep Sea habitat (>1000 m; Bathypelagic and Abyssopelagic habitats combined).

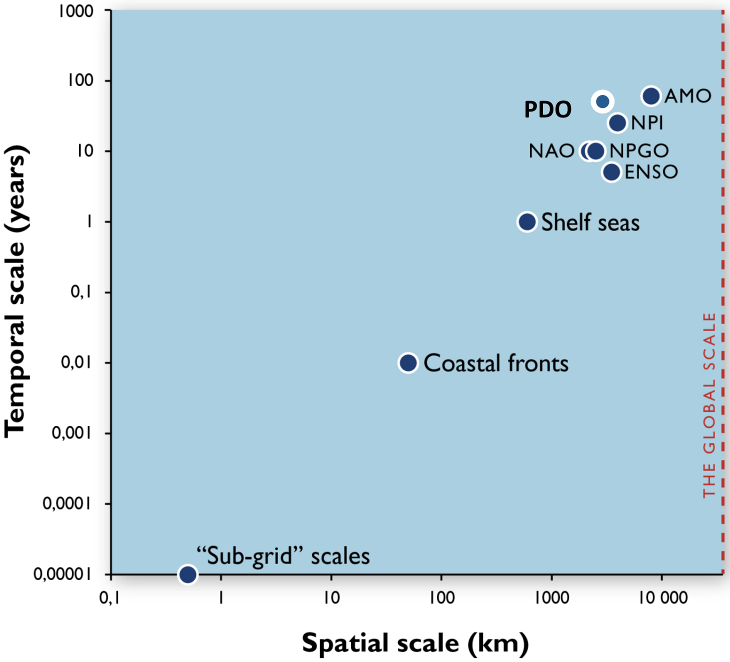


Figure 30-2: Spatial and temporal scales of climate-related phenomena within the world oceans (AMO: [*Sutton and Hodson*, 2005]; NPI: [*Deser et al.*, 2004]; NAO: [*Hurrell and VanLoon*, 1997]; NPGO: [*Di Lorenzo et al.*, 2008]}). The dotted line indicates the circumference of the Earth.

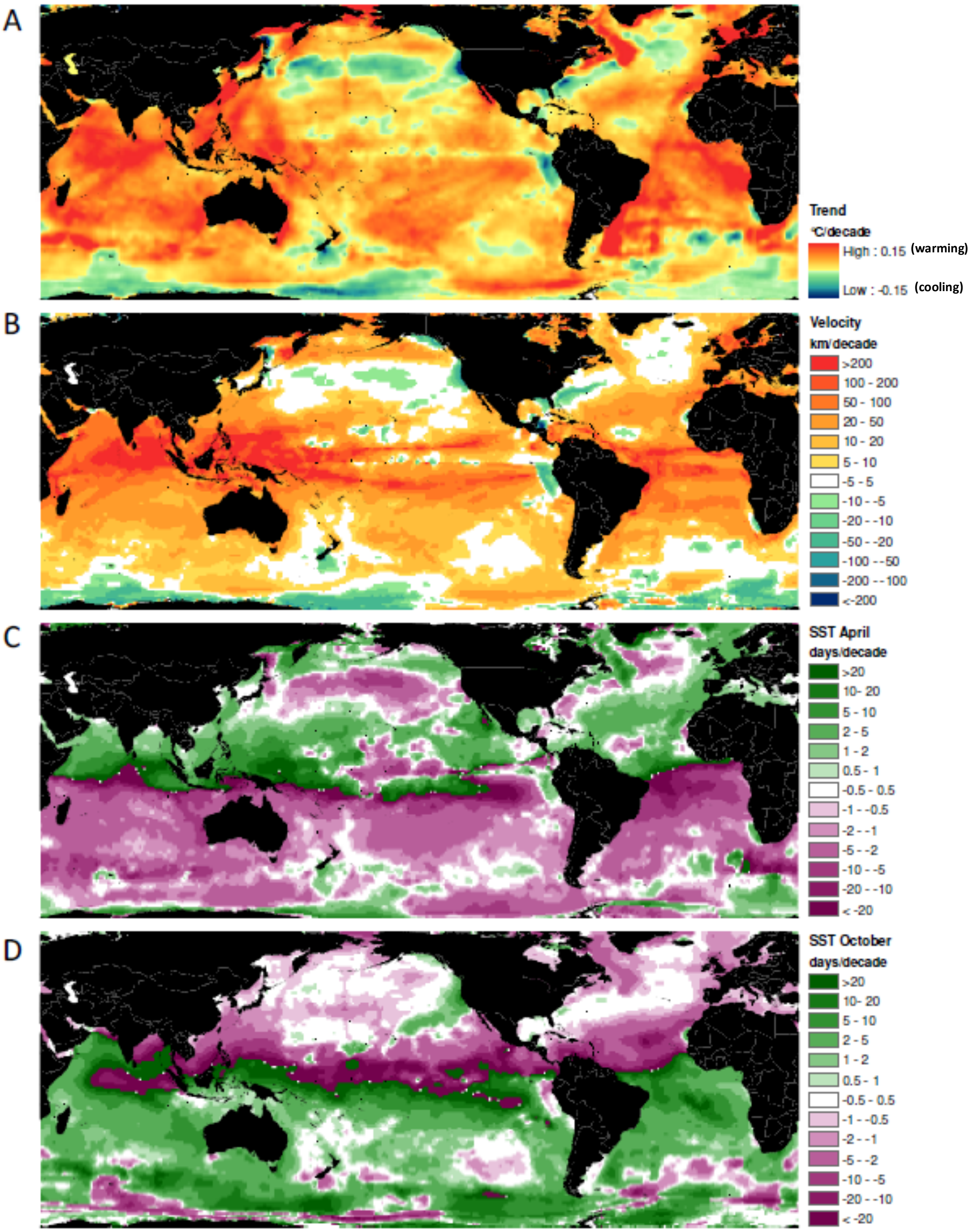


Figure 30-3: Analysis of data from Hadley Centre (HadISST 1.1) for different ocean regions. A. Rate of change in sea surface temperature over the past 30 years (°C. decade^{-1}). B. Velocity at which isotherms are moving (km.decade^{-1}) from 1960-2009. C. Shift in seasonal triggers (days.decade^{-1}) for April and D. for October.

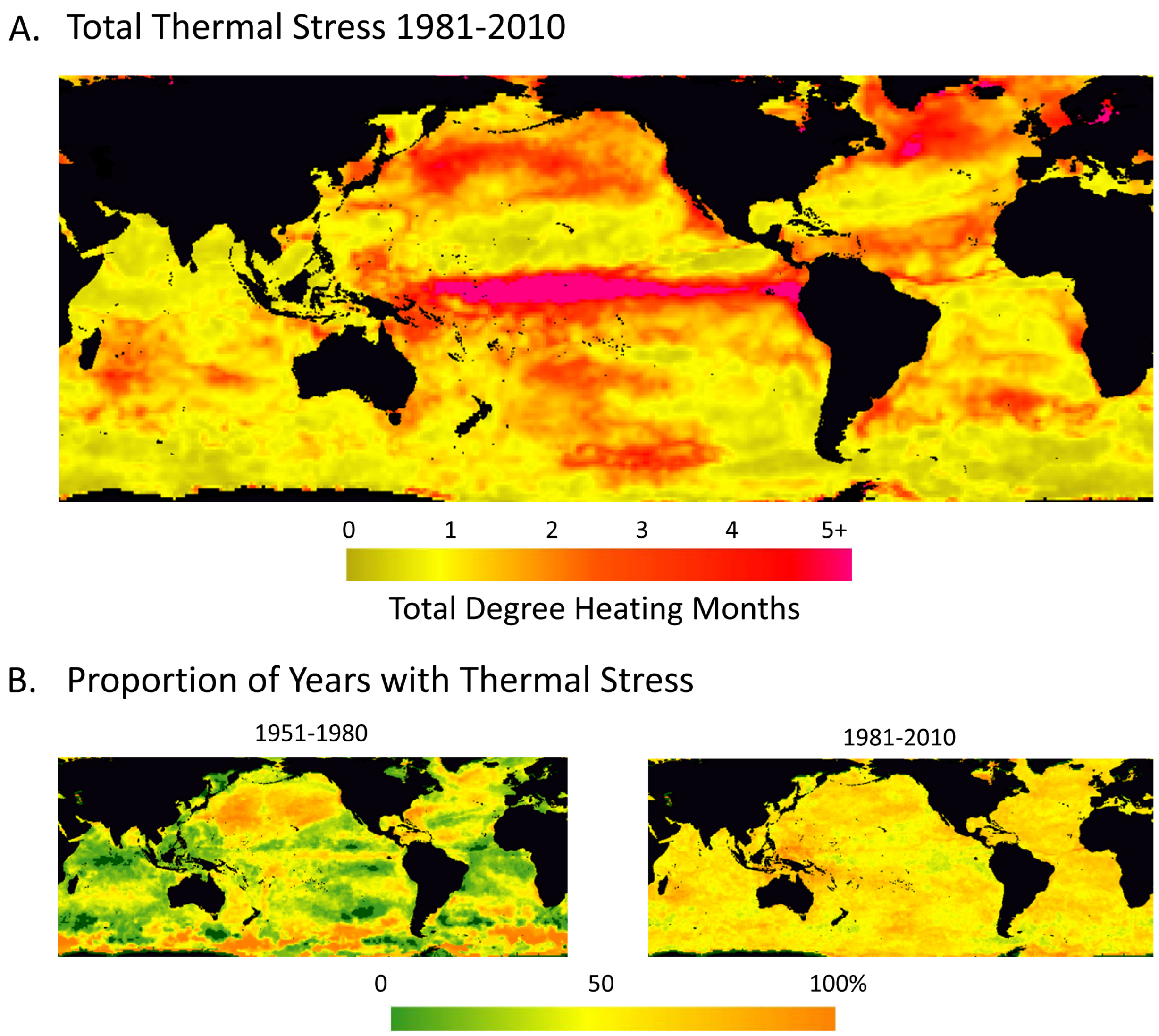


Figure 30-4: Recent changes in thermal stress calculating using HaddISST 1.1 data. (A) Total thermal stress for the period 1981-2010, calculated by summing all monthly thermal anomalies for each grid cell. (B) Proportion of years with thermal stress, which is defined as any year that has a thermal anomaly, for the periods 1951-1980 and (C) 1981-2010. Monthly anomalies were calculated using the maximum in the monthly climatology for each grid cell for the period 1985-2000 after Donner et al (2007).

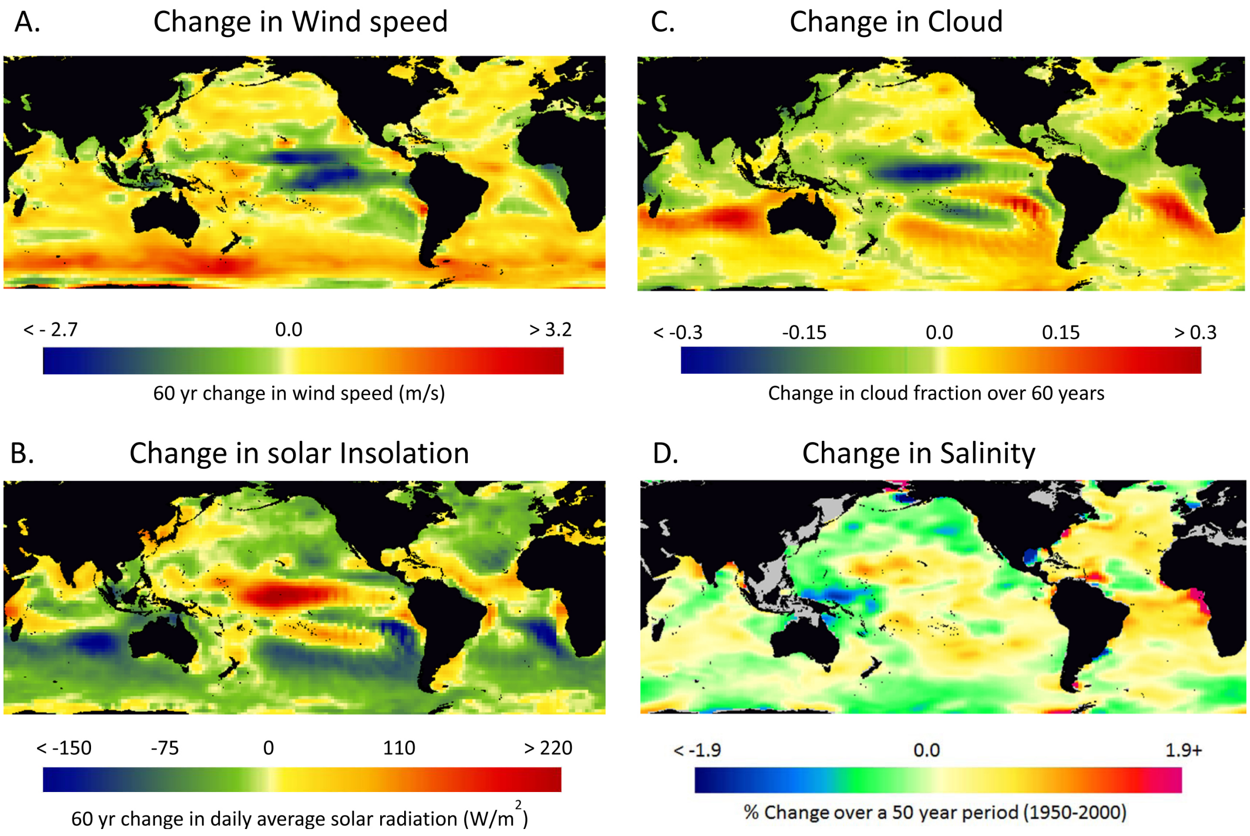


Figure 30-5: Absolute change from 1951-2010 in (A) Wind Speed as the absolute change in m.s^{-1}; (B) Solar radiation as change at the surface of incoming solar insolation in Wm^{-2}; (C) Cloud Cover as the absolute change in total cloud fraction (i.e. If at the beginning of the period the cloud fraction was 0.6 and 0.5 at the end of the period, the change would be -0.1) using NCEP re-analyzed data (www.esrl.noaa.gov); and (D) Salinity as the percentage change from 1960-2010 [*Durack and Wijffels*, 2010].

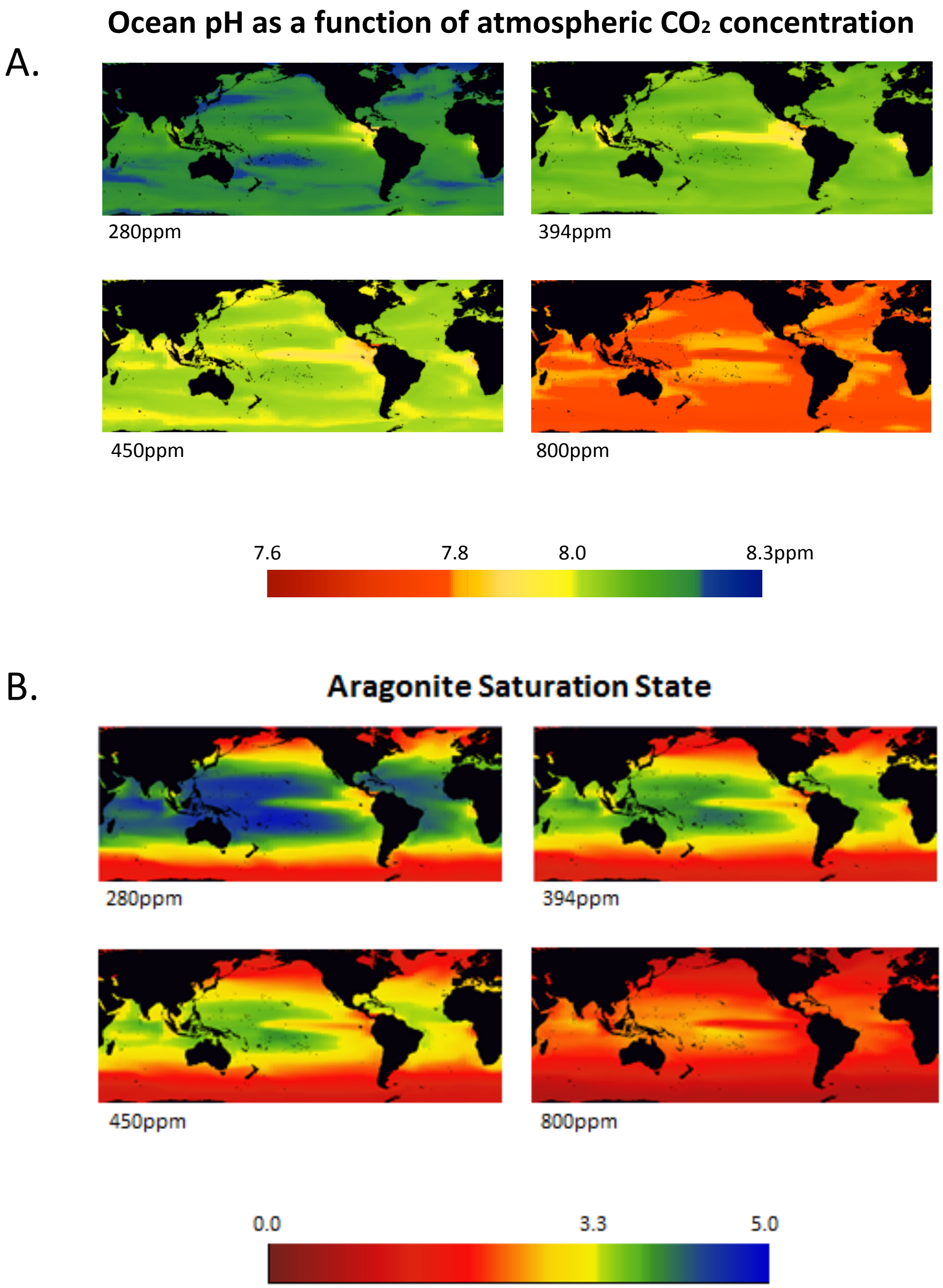


Figure 30-6: Surface ocean pH and aragonite saturation state at different atmospheric CO2 levels simulated by the University of Victoria Earth System Model. The fields of pH and aragonite saturation state are calculated from the model output of dissolved inorganic carbon concentration, alkalinity concentration, temperature, and salinity, together with the chemistry routine from the OCMIP-3 project (http://www.ipsl.jussieu.fr/OCMIP/phase3).

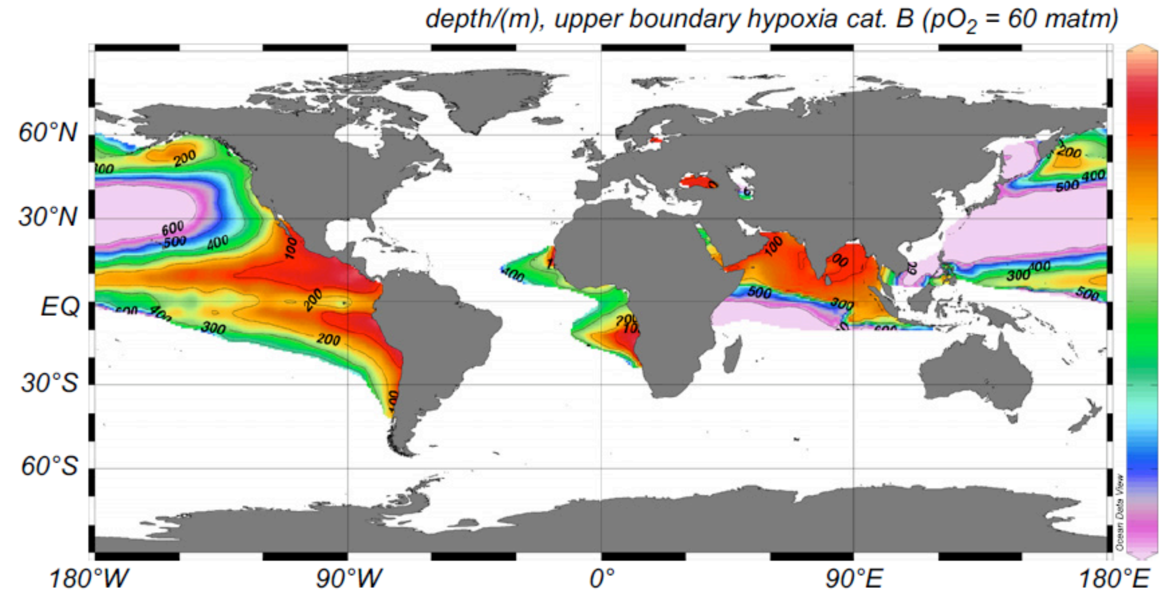


Figure 30-7: Map of the depth [*Hofmann et al.*, 2011] at which a critical value of partial pressure of O_2 of 60 matm occurs which is widely accepted as threatening to marine life on continental shelves (200m depth). Conventional maps of oceanic oxygen values report simple mass properties with no temperature or depth dependence; a better rendition of the availability of O_2 to marine life is provided by the partial pressure, which includes the temperature terms. The value of pO_2 equal to 60 matm reasonably follows the widely used limiting concentration value of 61 μmolar, or 2 mg O_2/l^{-1}. Critical regions in the eastern and northern Pacific and in the northern Indian ocean stand out. In these areas quite modest upward expansion of the depth at which the critical pO_2 level occurs can have negative effects on major fish populations. Note: not all areas have been included – for example, significant hypoxia in the Gulf of Mexico has not been shown.

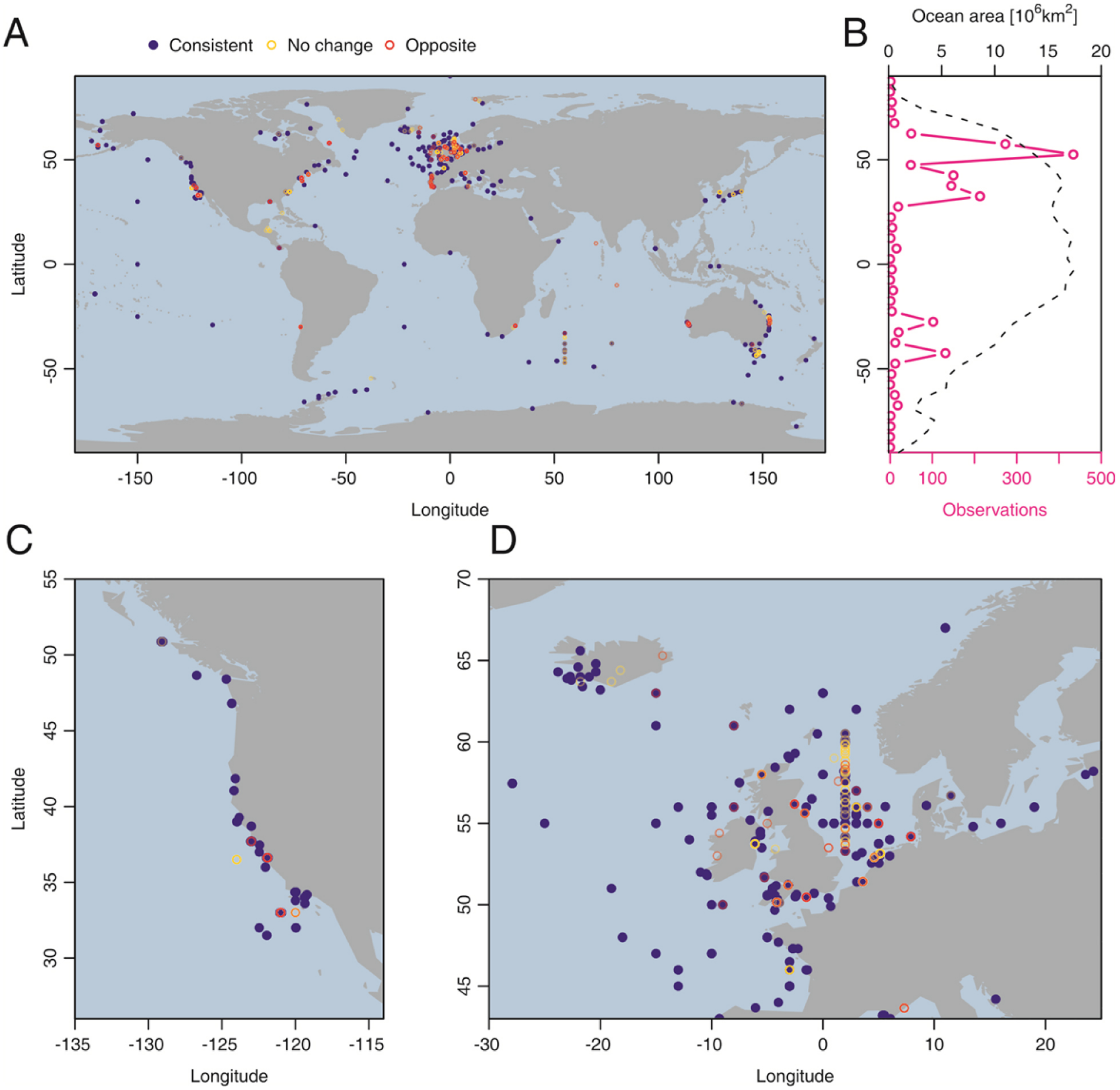


Figure 30-8: (A) Consistency of observed responses to climate change from 1701 single- and multi-species studies showing responses that are consistent with climate change (blue), opposite to expected (red) and are equivocal (yellow). Each circle represents the center of a study area. Where points fall on land, it is because they are centroids of distribution that surround an island or peninsula. (B) Frequency of observations by latitude. (C) Observations from the California Current (D) Observations from the northeast Atlantic (from Poloczanska et al 2012).

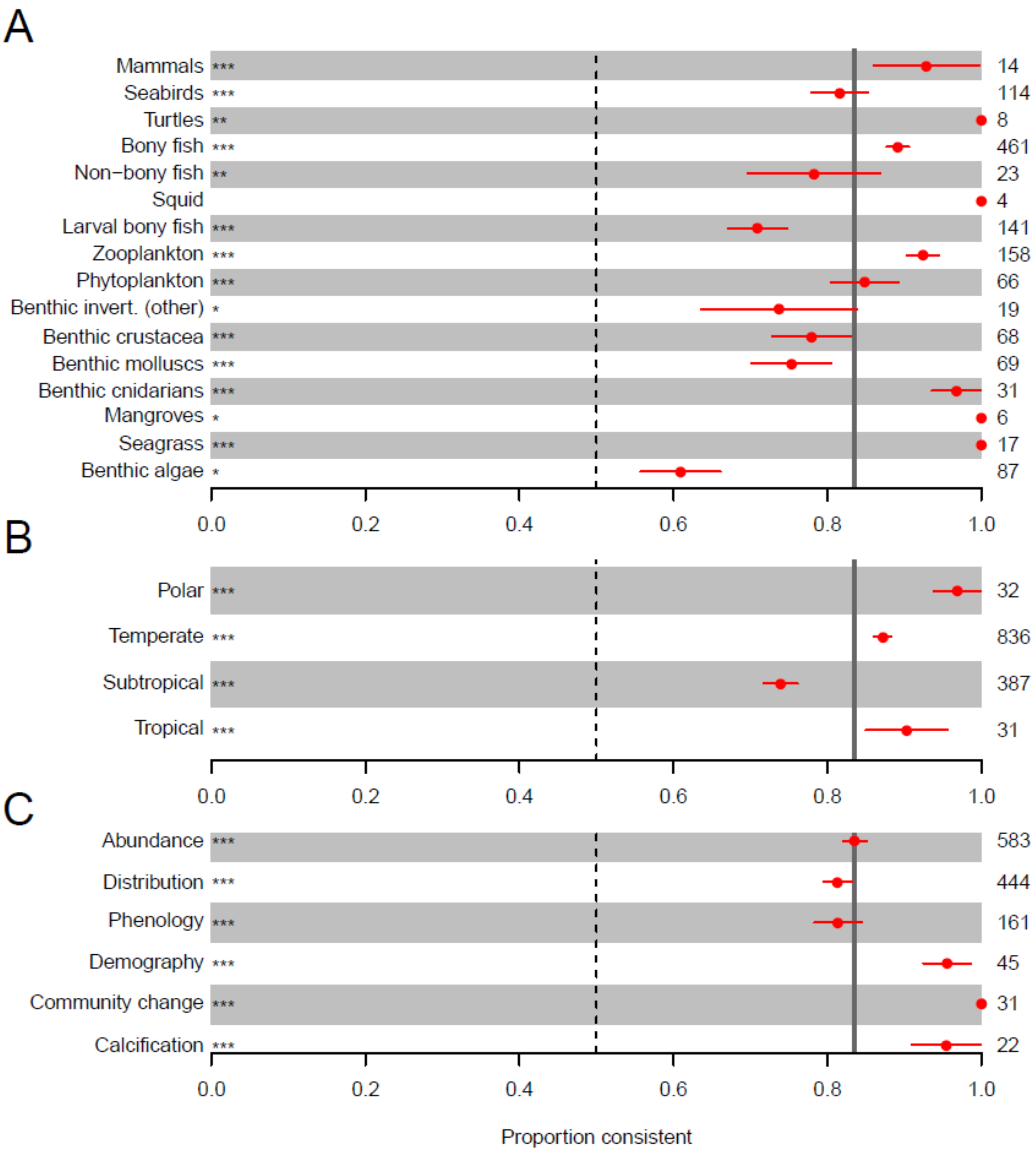


Figure 30-9: Percent of observations consistent with climate change predictions. Mean and standard error of responses by (A) taxa, (B) latitudinal region and (C) response measure show significantly higher consistency than expected from random (dashed line at 50% consistency). Solid line is the mean across all observations. Significance of results is listed next to labels (***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$). Sample sizes are listed to the right of each row.

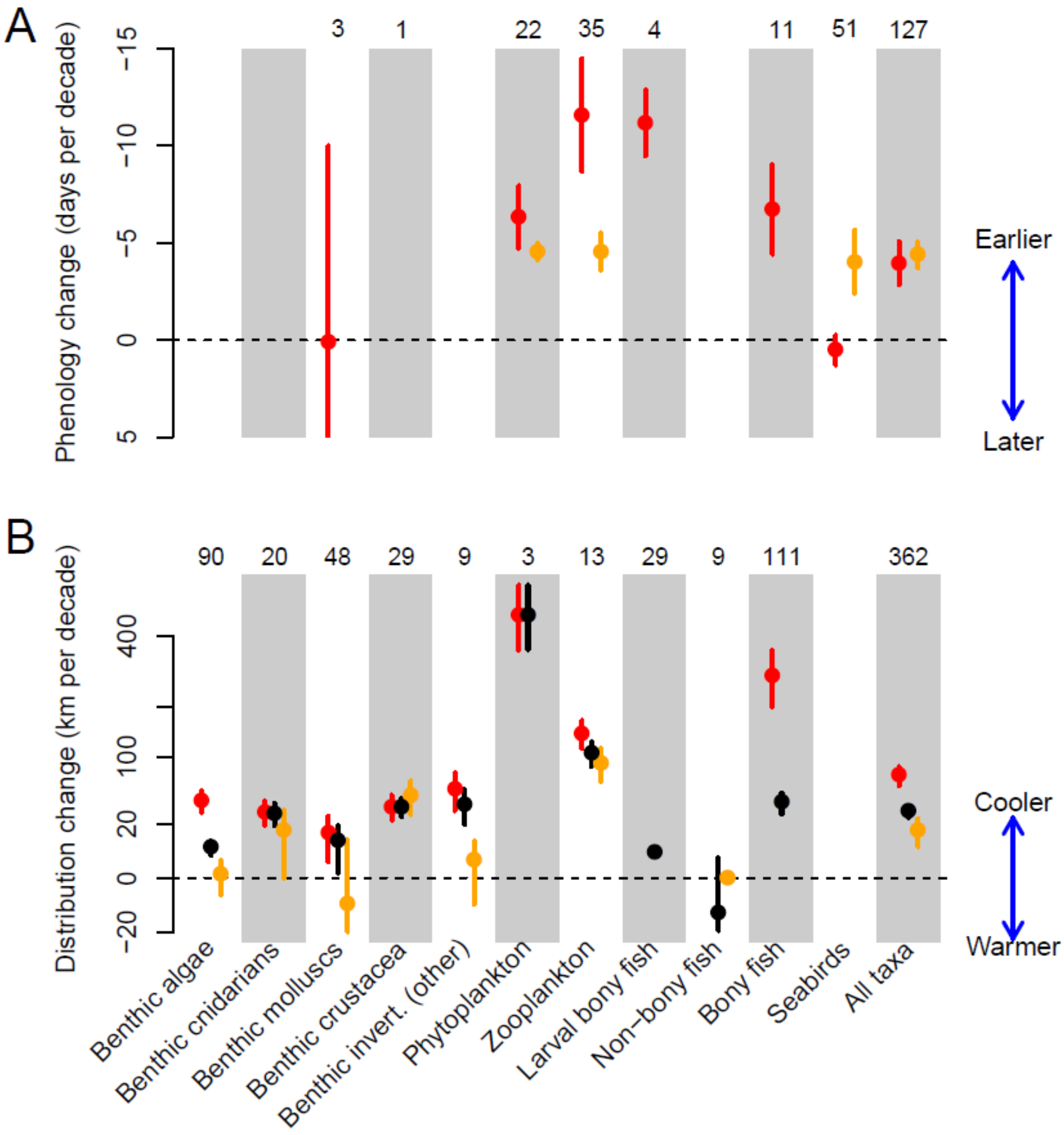


Figure 30-10: Rates of change in (A) phenology (days/decade^{-1}) measured during spring/summer (red) and autumn/winter (yellow); and (B) distribution (km/decade^{-1}) for marine taxonomic groups, measured at the leading edges (red), centers of distribution (black) and trailing edges (yellow). Distribution rates have been square-root transformed; standard errors may be asymmetric as a result. Positive distribution changes are consistent with warming (into previously cooler waters, generally poleward) and negative phenological changes are consistent with warming (generally earlier). Means ± standard error are shown, with number of observations and significance (*p<0.1, **p<0.05, ***p<0.01). From Poloczanska et al (2012).

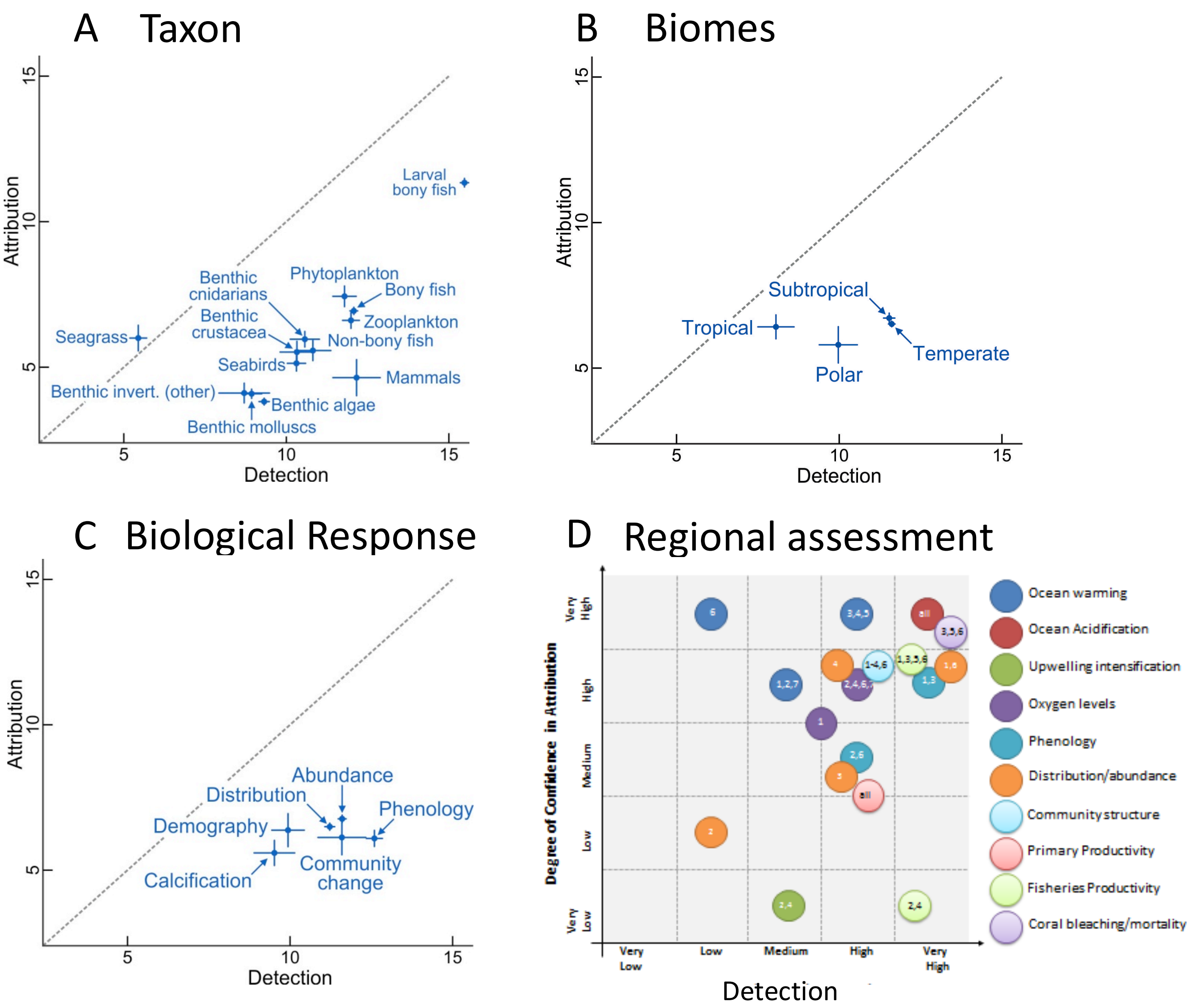


Figure 30-11: Quantitative evaluation of degree of confidence in the detection of change and attribution of observed change to climate change of 1701 of 838 species (Poloczanska et al. 2012) across A. Taxonomic groups, B. Biomes and C. Biological response (modified from O'Connor et al in prep). D. Expert assessment of degree of confidence in detection and attribution across regions and processes (based on evidence explored throughout Chapter 30).

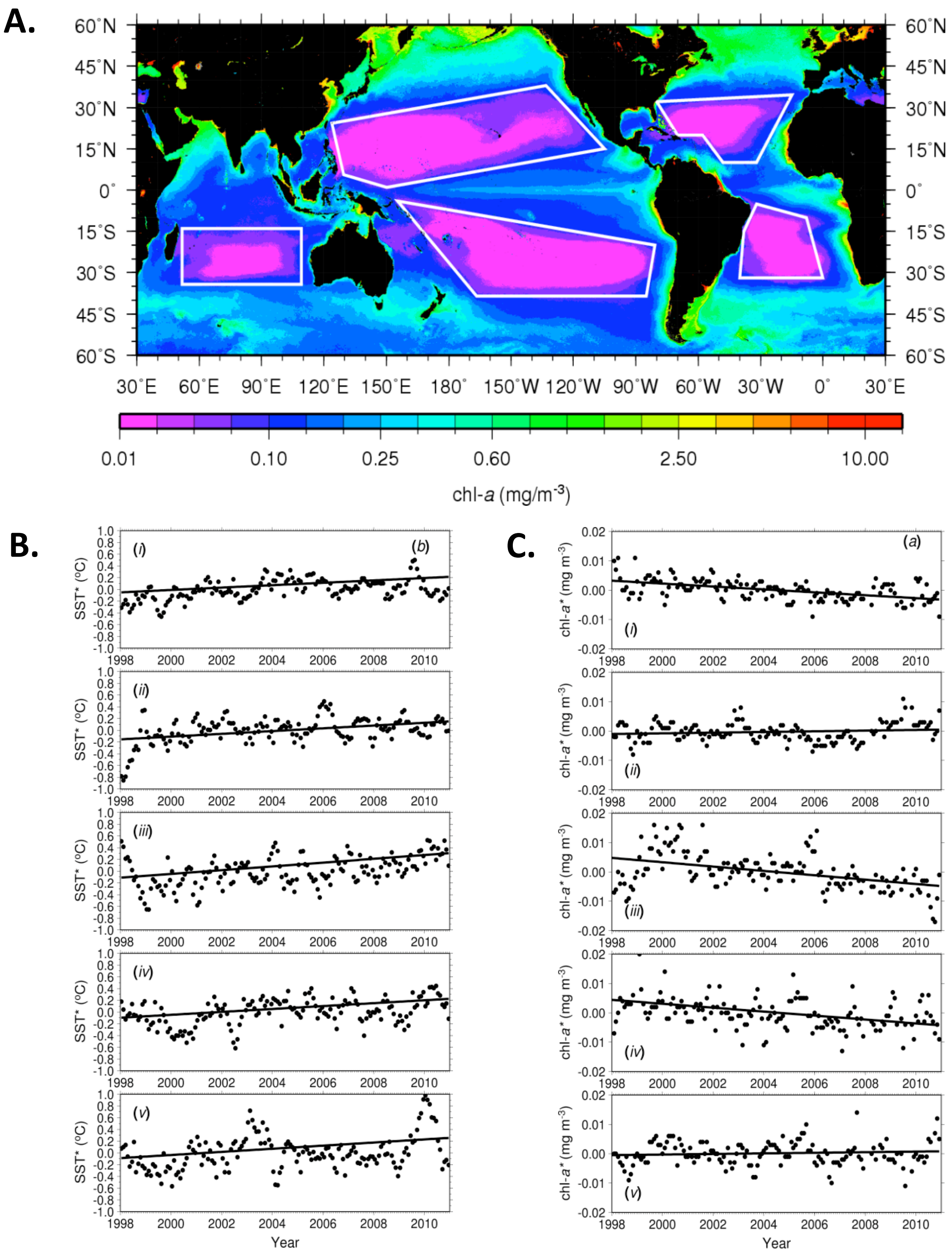


Figure 30-12: A. Map of SeaWiFS chl-a climatology. The white polygons define the regions that were analyzed and represent the major regions considered as sub-tropical gyres by Signorini and McClain (2012). B. Time series of anomalies in chl-a and B. Sea Surface Temperature SST for subtropical gyres in North Pacific (NPAC), South Pacific (SPAC), Indian Ocean (IOCE) North Atlantic (NATL) and South Atlantic (SATL) Oceans.

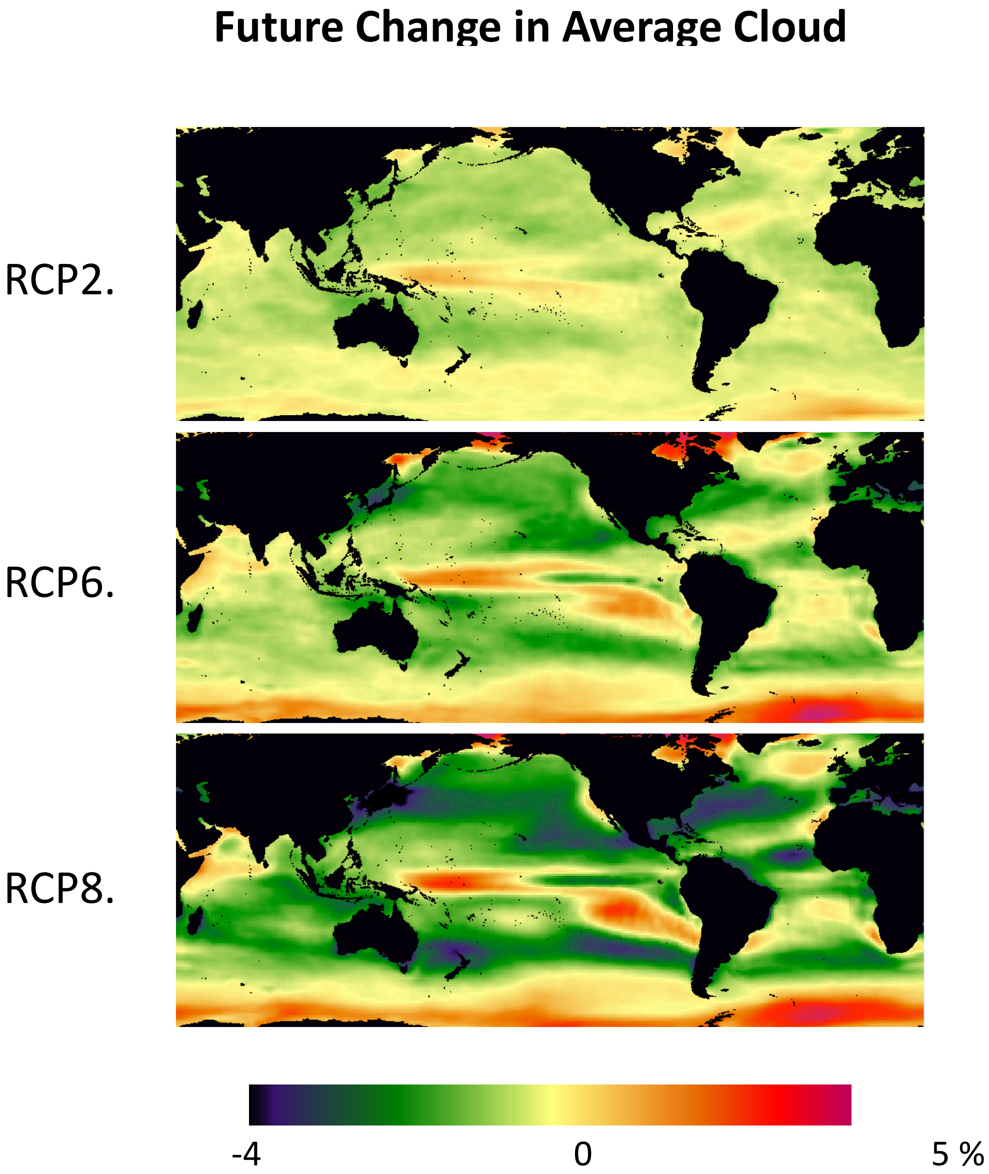


Figure 30-13: Change in cloud fraction for each of three CMIP-5 Representative Concentration Pathways (RCP 2.6, 6.0 and 8.5). For each pixel, these plots were derived by calculating the average monthly % cloud cover for the period 2006 – 2035 and subtracting it from the monthly average from 2070-2099. These values represent the absolute change in total cloud fraction (i.e. if the cloud fraction was 60% in 2006-2035 and 50% in the 2070-2099 period, the change would be a -10% change in average monthly cloud fraction)

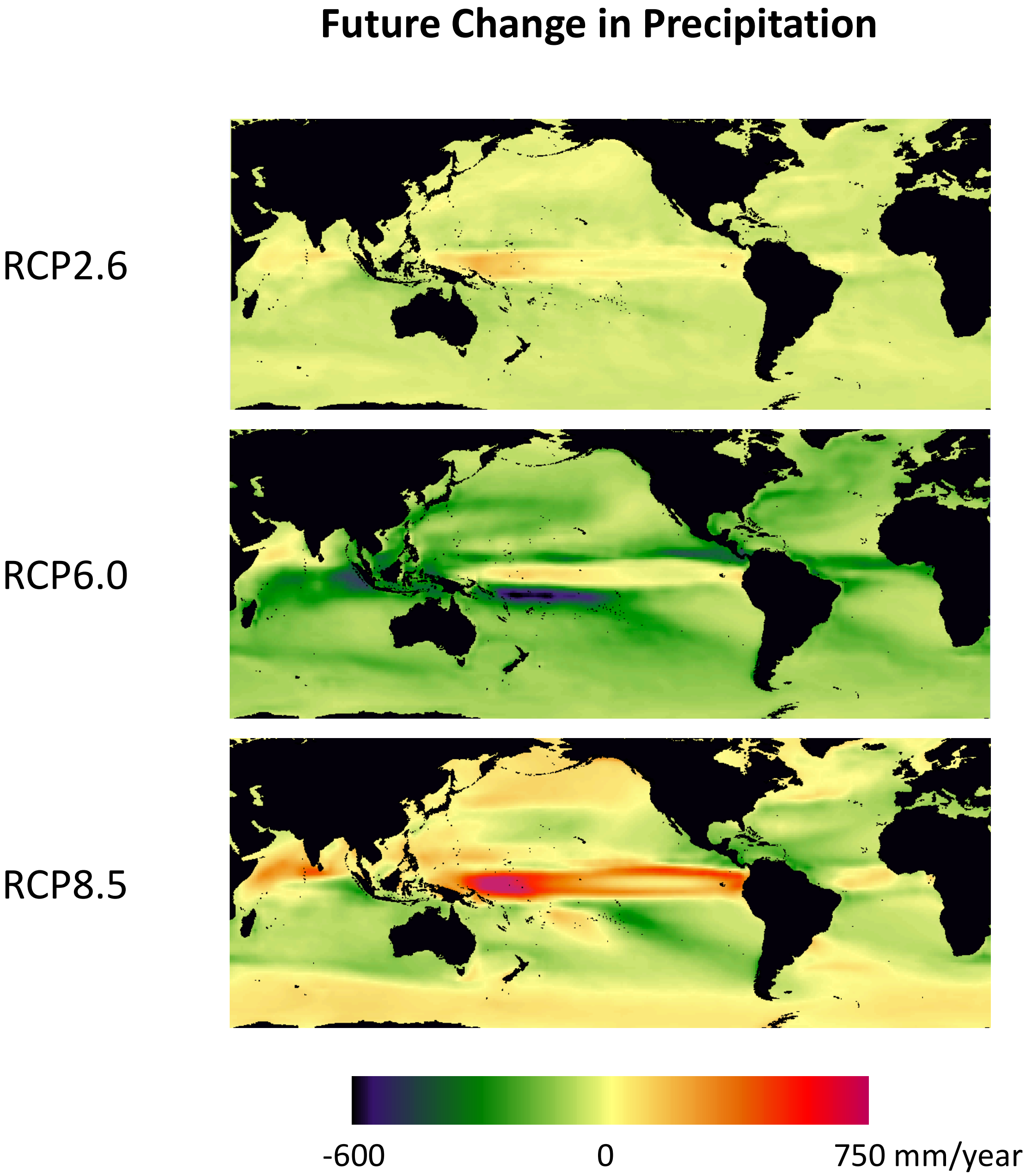


Figure 30-14: Change in precipitation for each of three CMIP-5 Representative Concentration Pathways (RCP 2.6, 6.0 & 8.5). For each pixel, these plots were derived by calculating the average monthly precipitation (mm/year) for the period 2006 – 2035 and subtracting it from the monthly average from 2070-2099 to provide a measure of the absolute change in precipitation over approximately the next 65 years.

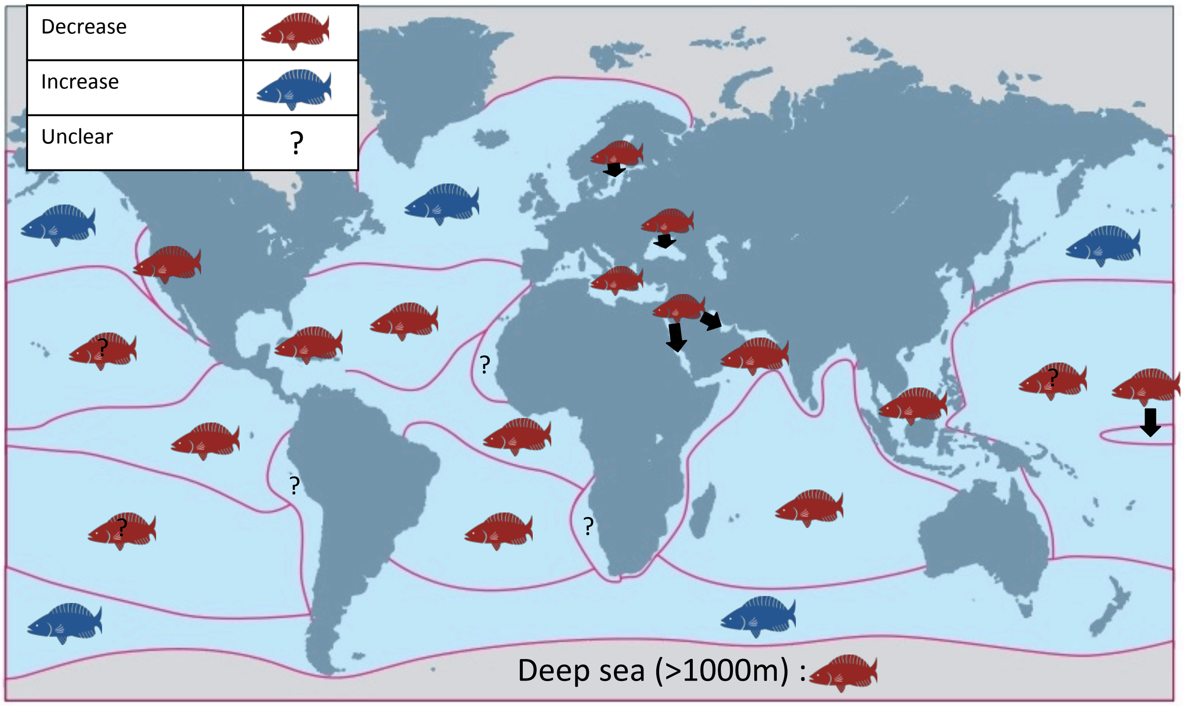
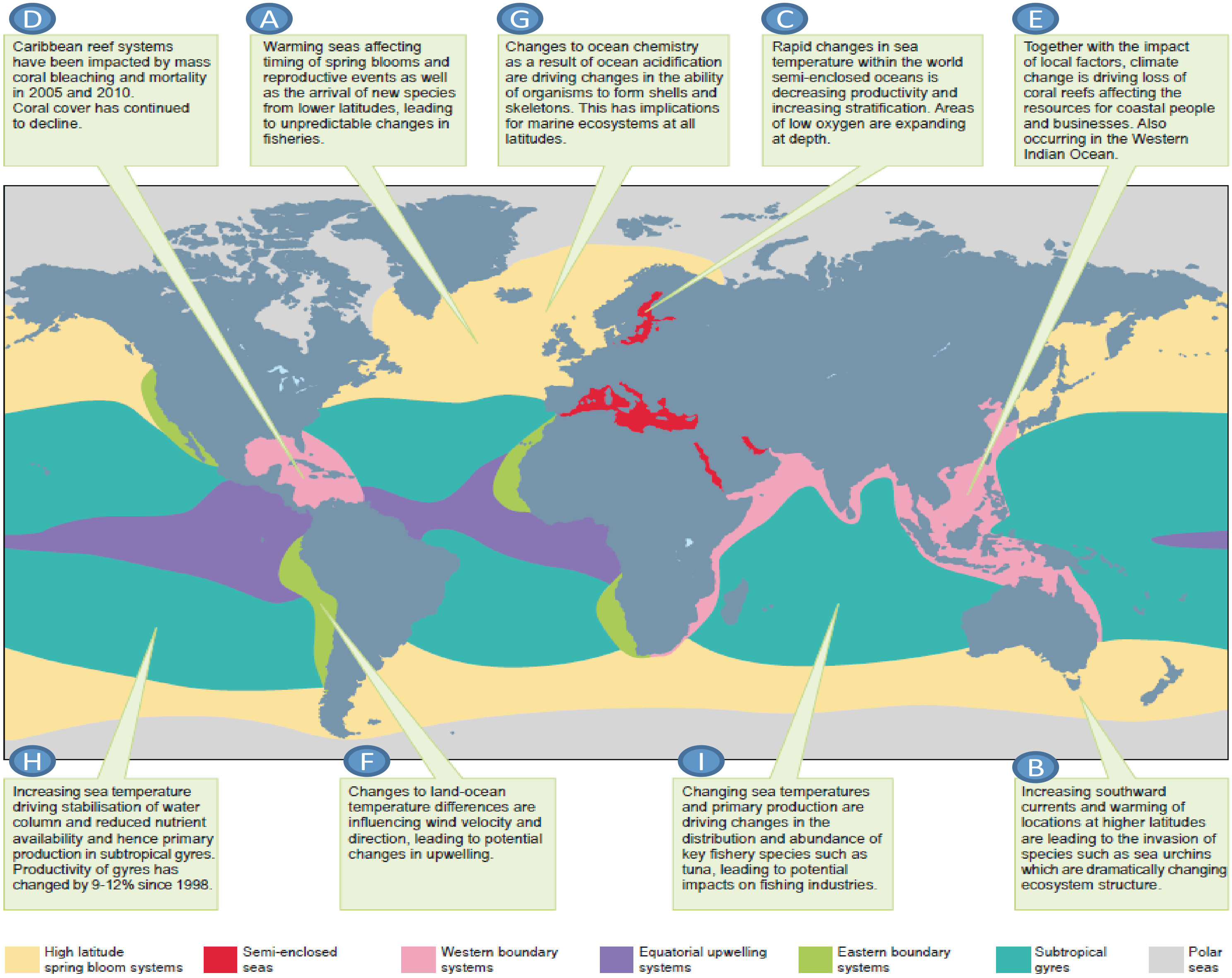


Figure 30-15: Expectations for major impacts of climate change on fishery catch potential by 2050, based on literature review in Chapter 30. Current and future fishery management status is not taken into account. Arrows indicate expectations in small regions. Climate change is expected to impact the ability of ecosystems to support fisheries in all major ocean regions. Predicting changes in fisheries catch is complicated by multiple effects of climate change on fish ecology and the confounding effects of changes in fishery management. However, we can generate some broad expectations about how climate change will impact the ability of ecosystems to support fisheries. Range shifts pole-wards of southern species and expanding ice free habitat may benefit fishery catch potential in high latitude regions, whereas, range shifts away from the equator may see declines in potential of tropical ecosystems to support fisheries (Cheung et al. 2010, Perry et al. 2010). Similarly, semi-enclosed seas may see losses in catch potential, due to geographic dead ends that hinder range shifts and increasing likelihood of anoxic zones (Cheung et al. 2010, Section 30.5.6). Loss of coral reef habitat in the tropics may also reduce fisheries catch potential. Recent observation and model predictions suggest declining primary production in subtropical gyres (Steinacher et al. 2010, Polovina et al. 2008), which may result in declines in fishery catch potential there, conversely, some models predict increases in Pacific tuna catch (Bell et al. 2011). Some of the world's most productive fisheries occur in Eastern Boundary systems. It is unclear whether climate change will cause increases or decreases in primary production and subsequently fisheries in these regions (Section 30.5.2). Deep sea ecosystems are extremely sensitive to rising temperatures and acidification (Section 30.5.7), so catch potential declines may be expected in these regions.



D: Caribbean reef systems have been impacted by mass coral bleaching and mortality in 2005 and 2010. Coral cover has continued to decline.

A: Warming seas affecting timing of spring blooms and reproductive events as well as the arrival of new species from lower latitudes, leading to unpredictable changes in fisheries.

G: Changes to ocean chemistry as a result of ocean acidification are driving changes in the ability of organisms to form shells and skeletons. This has implications for marine ecosystems at all latitudes.

C: Rapid changes in sea temperature within the world semi-enclosed oceans is decreasing productivity and increasing stratification. Areas of low oxygen are expanding at depth.

E: Together with the impact of local factors, climate change is driving loss of coral reefs affecting the resources for coastal people and businesses. Also occurring in the Western Indian Ocean.

H: Increasing sea temperature driving stabilisation of water column and reduced nutrient availability and hence primary production in subtropical gyres. Productivity of gyres has changed by 9-12% since 1998.

F: Changes to land-ocean temperature differences are influencing wind velocity and direction, leading to potential changes in upwelling.

I: Changing sea temperatures and primary production are driving changes in the distribution and abundance of key fishery species such as tuna, leading to potential impacts on fishing industries.

B: Increasing southward currents and warming of locations at higher latitudes are leading to the invasion of species such as sea urchins which are dramatically changing ecosystem structure.

Figure 30-16: Summary of regional impacts (and opportunities) of climate change on the world's open oceans.

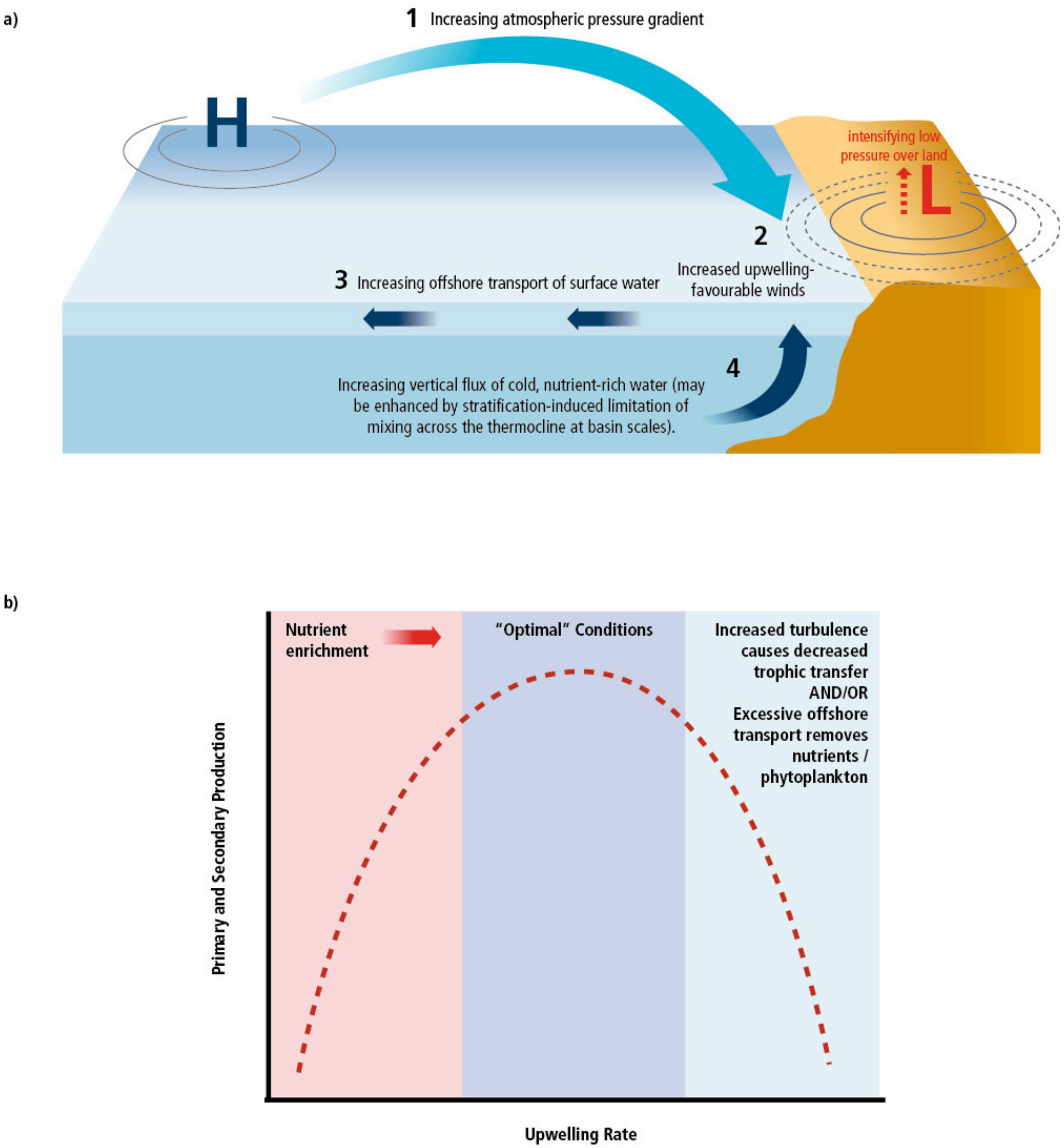
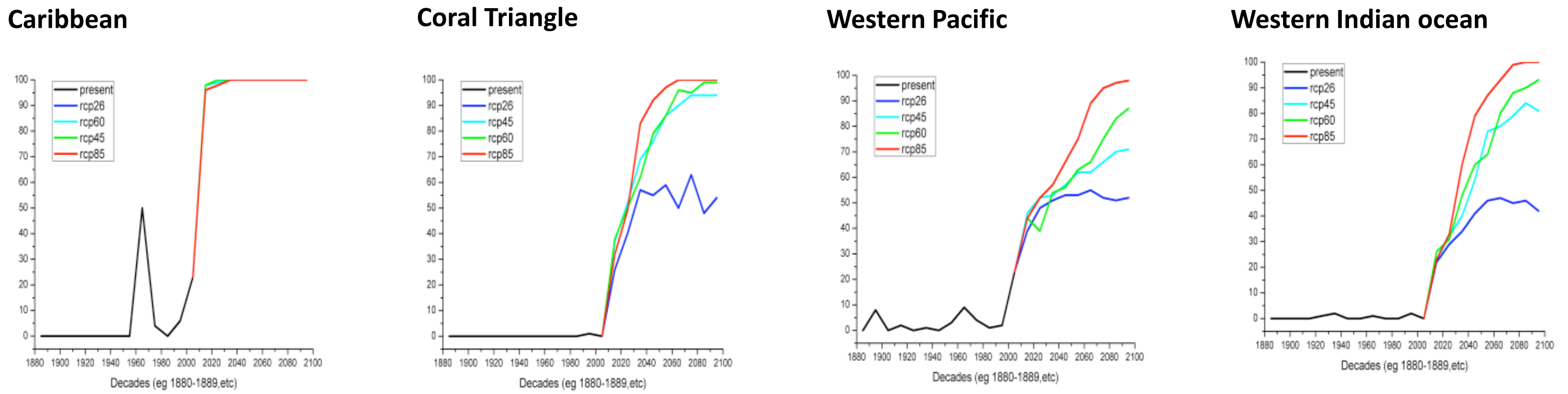


Figure 30-17: Diagrammatic representation of the interaction between land sea temperature, wind direction and strength, and coastal upwelling.

A. Average % of events per year of DHM 1 and above (representative of 'mass coral bleaching events')



B. Average % of events per year of DHM 5 and above (representative of 'mass coral mortality events')

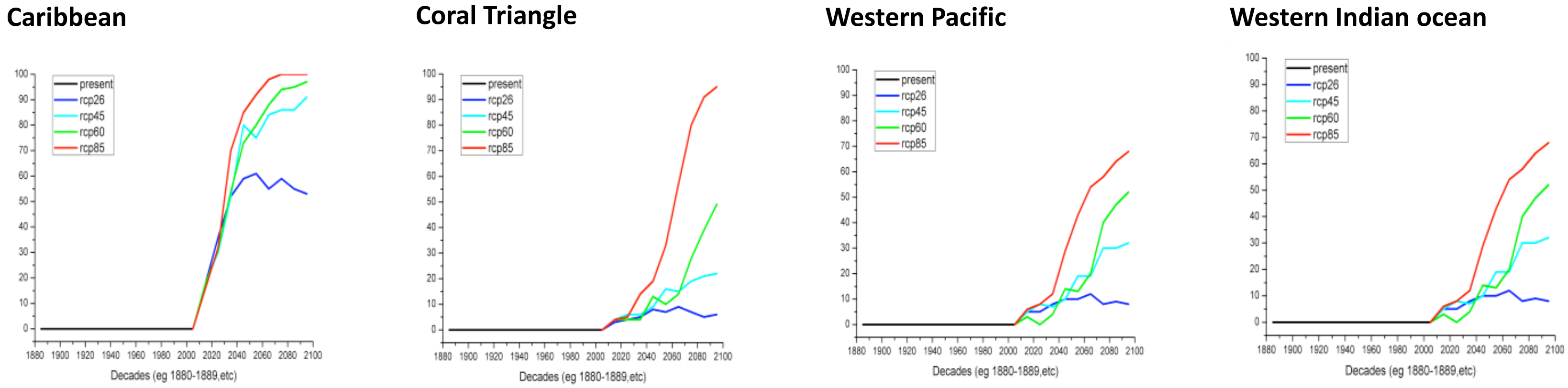


Figure 30-18: Average yearly percentage of occurrence of DHM ≥ 1 (representative of coral bleaching events) and DHM ≥ 5 (representative of mass coral mortality events) for the period 1980-2099 (with climatology and DHMs derived from HadISST 1.1 for 1880-2009; and for 2010-2099 the climatology was derived from CMiP-5 historic runs and modelled RCP 2.6, 4.5, 6.0 & 8.5 values were used to derive DHMs) in each of the four coral regions (Figure 30-1, Table 30-1). Degree Heating Months (DHM) can then be calculated by adding up the anomalies using a 4-month rolling sum (after Donner et al., 2007). A value of 50% means that the event is occurring once every two years on average, a value of 100% means that the event is occurring every year.

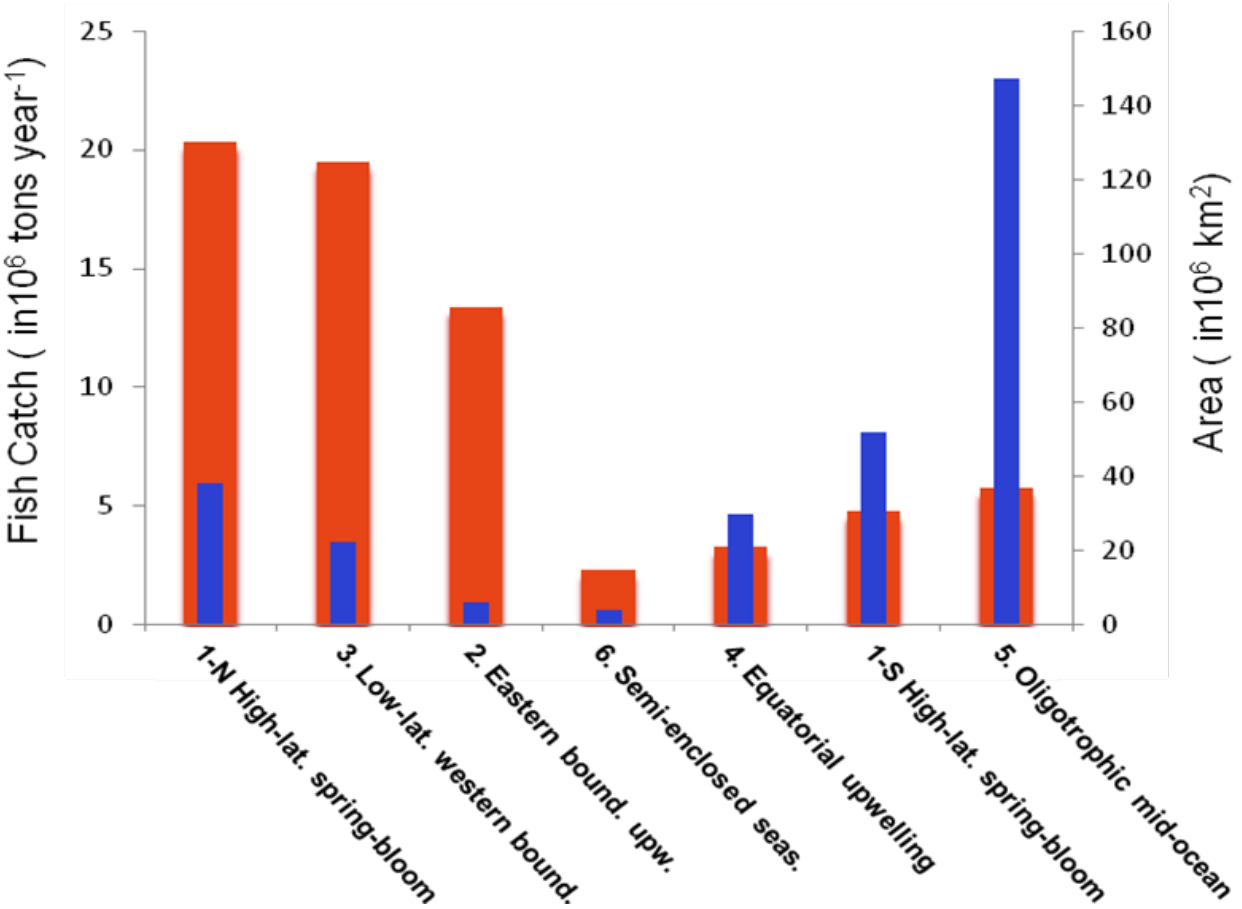


Figure 30-19: Fish catches and areas for ecosystem regions shown in Figure 30-1. Red columns: average fish catch (millions tons yr^{-1}) for the period 1970-2006. Blue columns: area (millions km^2).