Chapter 30. Open Oceans

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

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

Contributing Authors
Mark Eakin (USA), Ben Halpern (USA), Long Cao (USA), Chuck McClain (USA), Elvira Poloczanska (Australia), Anthony J. Richardson (Australia), Rui Zhang (China), Sergio Signorini (USA), William Skirving (USA)

Review Editors
Omar Ly (Senegal), Carol Turley (EC)

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Executive Summary

The Earth's ocean distinguishes our planet from thousands of others and is a critical part of our planetary dynamics, providing a range of planetary and ecosystem services. In concert with a series of local stresses, rising greenhouse gas concentrations are driving fundamental changes to the physical and chemical characteristics of the ocean (Ch3,WGI). Changes within the major ocean basins and semi-enclosed seas include increasing sea temperatures, acidity, and sea levels, and changes to the intensity of currents, vertical mixing, and water column stability (increasing or decreasing depending on location). The latter are changing the degree of ocean mixing in the upper layers of the ocean which along with changing oceanic conditions for metabolic processes (as a result of increasing temperature), are leading to fundamental changes in the oxygen content of some regional seas and coastal areas. This is leading to a highly significant decrease in oxygen concentrations within the ocean interior. These changes are occurring at different rates in different ocean basins, and are showing some of the highest rates in the world's semi-enclosed seas such as the Arabian Gulf, Mediterranean, Baltic and North Seas (although the latter is a shallow shelf sea with strong ventilation).. A comprehensive assessment of the biological changes that have been occurring in the ocean has revealed that the majority of studies on marine organisms and ecosystem processes are consistent (> 74% of 2,006 reports) with the direction expected under rapid climate change and ocean acidification. Within this overwhelming tendency for biological systems to respond to climate change and ocean acidification, are responses in the distribution and abundance of marine organisms, community structure, demography, phenology, and ecological processes such as primary production, respiration and calcification. Investigation of these trends within the world's ocean basins revealed major changes in the Atlantic, Indian, and Pacific oceans, along with some profound changes in semi-enclosed oceans such as the Arabian Gulf, Mediterranean, Baltic and North Seas. These changes have already begun to affect the ability of ocean ecosystem services to provide support to human industries and communities. Interaction between global and local factors are driving major changes in the distribution and abundance of fisheries resources, with many close to collapse. It is important to note that past fish stock collapses have generally been caused by overfishing which is often accelerated by climate variability. Other industries such as tourism along the world's coastlines are changing fundamentally, although it is unclear whether or not these changes will impact on the ability of coastlines to support tourism. Short-term projections indicate major changes within tropical coastal ecosystems, especially with respect to key ecosystems such as coral reefs, mangroves, and sea grass beds which will be under increasing pressure from increasing sea temperatures, changing water chemistry, and rising sea levels. The biodiversity value , as well as goods and service provided by many ecosystems will be substantially compromised as carbon dioxide concentrations continue to rise in Earth's atmosphere. At longer-term horizons, many fisheries, along with productive ecosystems such as coral reefs, are very likely to change beyond recognition, with substantial impacts on coastal societies throughout the world. These changes will also interfere with the ability of the ocean to provide planetary services such as regulation of atmospheric gas concentrations and carbon sequestration.

30.1. Introduction

Oceans occupy around 71% of the Earth's surface and 97% of the global water inventory, with 80% of the surface water flux occurring over the oceans. Stretching from the high tide mark to the open oceans, this vast region has a dominant influence on the atmosphere, and is the major sink for heat and carbon dioxide. Winds combined with differential heating between land and ocean waters drive regional weather patterns. Ocean waters occupy 1.3 billion km^3 with an average depth of over 3.5 km and include the Pacific, Atlantic, Indian, Southern and Arctic oceans [*Stewart and Texas*, 2004]. This chapter focuses on the three primary ocean basins, Pacific, Indian and Atlantic Oceans, and their associated semi-enclosed seas (Figure 30-1). The Southern and Arctic Oceans are included in Chapter 28 (Polar Regions) and are not discussed here.

[INSERT FIGURE 30-1 HERE
Figure 30-1: Title TBD. [*Placeholder - (Needs to be replaced by the appropriate reference and summary datasets from WG1 CH3): (a) Average annual sea surface temperature, (b) surface salinity; (c) pH of the global ocean, and (d) change in carbonate ion concentration since the beginning of the industrial revolution. If possible have maps extend from Africa to Africa in order to keep three ocean basins clearly visible and intact. Need to get appropriate and referenced figures from WG1.*]

Conditions within the world's oceans vary as a function of latitude, depth, water movement, and their proximity to landmasses. Ocean salinity ranges between 30 and 38 and temperature from -1.9°C to 35°C (Figure 30-1). Differences in the temperature, salinity, and pressure of the ocean also determine the solubility of carbon dioxide and consequently other properties such as pH and carbonate chemistry, which varies from 7.2-8.2 and 5-300 mmol kg^{-1}, respectively (Box 3.2, WGI; Figure 30-1).

The wind and tidally-forced movement of water within the ocean basins as well as the thermohaline circulation forced by solar heating and low latitudes and convection at high latitudes, plays a dominant role in determining ocean conditions and adjacent landmasses. Influenced by the Earth’s rotation, the major sub-tropical gyres of the three large oceans circulate in an anticyclonic direction implying clockwise circulation in the northern and anticlockwise circulation in the southern hemisphere (Figure 30-2).

[INSERT FIGURE 30-2 HERE
Figure 30-2: Title TBD. [*Placeholder - Major currents ... something like these ... shaded regions represent areas covered in chapter 30 - again tries to be consistent with Figure 30-1 - Africa to Africa orientation. Possibly with ocean gravity-large scale sea floor features as base map – get artist to make this figure eventually)*]

Conditions within the ocean vary with water depth. Light penetrates significantly into the upper 100 m of the open oceans (in the clearest conditions), driving the photosynthetic activity of organisms such as phytoplankton, marine angiosperms and macroalgae [*Lalli and Parsons*, 1993]. Energy harnessed during photosynthesis powers ocean food webs that ultimately support fisheries, although there are large variations among species, trophic structure, climatology and ecosystem structure. Most of the ocean, however, lies beyond the reach of sunlight. Deepwater habitats dominate, with more than 50% of the ocean is deeper than 3.7 km. The majority of the organic matter produced is recycled close to the surface; only a small fraction falls into deep waters. Organisms at these dark depths depend on either organic matter sinking from the photic zone, or on chemosynthesis associated with hydrothermal and cold vent communities. Deep ocean waters formed in polar regions are much cooler than the surface, ranging from -1 to 4°C. The dominance of respiration at depth results in higher concentrations of carbon dioxide, lower pH and reduced carbonate ion concentrations. Consequently, the precipitation of calcium carbonate becomes increasingly difficult, and carbonate skeletons of dead organisms rapidly dissolve [*Caldeira and Wickett*, 2003].

Approximately half of the Earth’s primary production occurs in the oceans (Field *et al.* 1998). As on land, marine ecosystems vary from highly productive examples such as upwelling areas, coral reefs and mangrove forests to regions with contrastingly low productivity such as the oligotrophic open ocean. At large ecosystem scales, there is good agreement between primary productivity and the productivity of higher trophic levels [*Richardson and Schoeman*, 2004] up to the harvestable resources [*Chassot et al.*, 2007; *Chassot et al.*, 2010; *Ware and Thomson*, 2005].

Highly productive regions of the world's oceans are found in upwelling regions near the ocean eastern boundaries (Figure 30-3). The five major upwelling ecosystems are the Humboldt and California Currents in the Pacific Ocean, the Benguela and Canary Currents in the Atlantic Ocean, and the seasonal monsoon-driven Somali Current in the Indian Ocean. Other regions of high productivity are the spring-bloom ecosystems in the northern North Pacific and the northern North Atlantic and the Southern Ocean adjacent the Antarctic continent [*Coale et al.*, 2004; *Field et al.*, 1998; *Palter et al.*, 2010]. At low latitudes, there is elevated primary productivity as a result of equatorial divergence of surface waters. "Oceanic deserts" form the central parts of the ocean gyres in the southern and northern hemispheres where the primary production is strongly limited by thermal stratification and relatively weak wind mixing, which results in slow vertical transport of nutrient-rich water from the deeper layer up into the euphotic zone (Figure 30-3).

[INSERT FIGURE 30-3 HERE
Figure 30-3: Global annual primary production (gC m^{-2} yr^{-1}). Total estimated production is 104.9 $x10^{15}$ gC yr^{-1} of which 46.2% in the ocean (after Field et al., 1998).]

In addition to impacts from anthropogenic climate change, ocean ecosystems are under stress from human activities such as the harvesting of living resources, habitat destruction, mineral extraction, shipping, offshore energy production, aquaculture, eutrophication, pollution, invasive species, ocean dumping and increased UV radiation from ozone depletion. Most of these activities mainly affect coastal shelf and inland seas, although persistent organic pollutants can have far reaching impacts [*Halpern et al.*, 2008]. Fishing activities in combination with climate variability and change are the factors that mostly influence abundance, distribution and health of marine organisms [*Harley et al.*, 2006]. The fishing pressure of world's marine ecosystems has increased substantially throughout the second half of the 20th century, from 20 million tons in 1950 peaking to 96 million tons in 2000 (FAO, www.fao.org). Thereafter, fish catches have declined to below 90 million tons at present. Many of the fishing regions are today overexploited, particularly with respect to the top predator species [*Myers and Worm*, 2003; *Pauly et al.*, 1998], although exploitation rates in 7 of the worlds 10 best-studied marine systems are now below estimated sustainable levels [*Worm et al.*, 2009]. However, many stock sizes still remain small and 63% of the assessed fisheries require rebuilding [*Worm et al.*, 2009]. Fisheries management is in the process of refocusing on ecosystem-based management, whereby combined fisheries and conservation objectives are considered. There is increasing appreciation that the carrying capacity of marine ecosystems is governed by the productivity at lower trophic level and from ocean climate forcing.

Circulation within each basin creates nutrient-rich, but oxygen-deficient and highly CO_2-enriched waters along the eastern margins. The highly nutrient loads of these up-welling waters boost primary productivity and support important commercial fisheries. Although upwelling regions occupy less than 0.1% of ocean surface area, yet they account for about 25-50% of global fisheries landings, thus impacts on upwelling systems, are of concern. But the lower oxygen and higher CO_2 of upwelling waters can also create major fish kills and cause economic harm [*Bakun and Weeks*, 2004; *Grantham et al.*, 2004; *Weeks et al.*, 2004].

Chapter 30 focuses on the ocean as a major geographic region with respect to the impact of climate change across the three major ocean basins (Atlantic, Indian, and Pacific Oceans) and the semi-enclosed seas such as the North, Baltic, and Mediterranean Seas. In doing so, this chapter brings together the physical, chemical, biological, and human aspects and impacts of climate change, and explores the broader picture of how the future is likely to unfold for these important oceanic regions. The integrated perspective of the Earth's ocean basins in the context of climate change is a new treatment in AR5 and recognizes the critical importance of the world's oceans to physical, chemical and biological conditions on Earth. Further, it has been recognized since AR4 that the biological impacts of climate change on marine systems was under reported [*Richardson and Poloczanska*, 2008].

There are numerous challenges in bringing together the observed and predicted regional impacts of climate change and ocean acidification within the ocean basins. The first is making decisions on how to proceed. In this respect, assessing which primary drivers are important, and the time and space scales over which they operate, is seen as important up front. The fragmentary nature of ocean observing, the uncertainty of model projections, and the challenge of attribution of observed changes to climate versus other impacts of mankind [*Hoegh-Guldberg et al.*, 2011; *Parmesan et al.*, 2011] such as coastal development, over fishing, and the impact of annual and decadal scale natural physical cycles on ecosystems (e.g [*Mantua et al.*, 1997] must all be taken into account. These local drivers occur to different degrees within each ocean basin or semi-enclosed sea.

30.2. Major Conclusions from Previous Assessments

A regional perspective on the changes and impacts on the major oceans was not undertaken in AR4. The previous assessment report concluded, however, that while terrestrial regions are warming faster than the oceans, observation since 1961 reveal that the average temperature of the global ocean has increased to depths of at least 3000 m due to the ocean taking up over 90% of the heat being added to the climate system by anthropogenic sources of greenhouse gases (WGI Ch3). The warming of the ocean through thermal expansion has contributed to sea level rise in addition to contributions from melting glaciers and ice caps. AR4 also concluded that “very likely that up to the end of the 20th century the Meridional Overturning Circulation (MOC) was changing significantly at interannual to decadal time scales” but noted that “over the modern instrumental record no coherent evidence for a trend in the mean strength of the MOC has been found”. Rising atmospheric carbon dioxide has produced 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 with the lowest decrease (0.06) in the tropics and subtropics, and the highest decrease (0.12) at high latitudes, consistent with the lower buffer capacity of the high latitudes compared to the low latitudes." A range of impacts on ocean ecosystems was also noted, particularly coral reefs and other coastal ecosystems which are experiencing a number of impacts from warming and acidifying ocean waters, sea level rise, and changing weather patterns.

30.3. Observed Impacts of Climate Change on the Ocean Basins and Semi-Enclosed Seas

Sea surface temperature of the global ocean has increased by about 0.5ºC during the 20th century [*IPCC*, 2007b]. Recent studies after release of IPCC AR4 verified the warming trend in the ocean by using various data sets and analyzing techniques [*Levitus et al.*, 2009; *Lyman et al.*, 2010; *Wijffels et al.*, 2008]. Warming in deeper waters was also observed but is slower. The global average warming over the past 50 years is about 0.1 ºC per decade in the surface and decreases to 0.017ºC per decade at 700 m [*Levitus et al.*, 2009]. Changes are greatest in the northern hemisphere and at high latitudes [*Levitus et al.*, 2009].

Information is limited on how marine ecosystems (relative to terrestrial studies) have responded to this long-term climate change [*Hoegh-Guldberg and Bruno*, 2010; *Richardson and Poloczanska*, 2010; *Richardson and Poloczanska*, 2008]. On a regional scale, however, there is increasing information on how marine ecosystems have responded to multi-decadal- and decadal-scale climate fluctuations. Such responses, particularly the responses to multi-decadal climate fluctuations, are of potential importance since they have spatial and temporal scales and rates of change close to those of projected anthropogenic climate change during the 21st century. Two prominent examples of such fluctuations are the Pacific Decadal Oscillation (PDO) with a periodicity of 20-30 years and the Atlantic Multi-decadal Oscillation (AMO) of periodicity 50-70 years. The PDO caused several dramatic shifts in the marine ecosystem of the North Pacific in the 20th century [*Mantua and Hare*, 2002; *Mantua et al.*, 1997]. The AMO resulted in warming in the entire North Atlantic Ocean during the mid 20th century and at the end of the century with cool periods between. The warm phases of the oscillation resulted in northward displacement species habitats from plankton to fish ([*Beaugrand*, 2005; *Beaugrand and Reid*, 2003; *Beaugrand et al.*, 2002](but see [*Poloczanska et al.*, 2011]). Climate events of shorter periodicity such as the El Niño Southern Oscillation (ENSO), Benguela Niños, and the North Atlantic Oscillation (NAO) also strongly impact marine ecosystems, although differently, partly because the changes are more abrupt and partly because climate variables other than temperature are also causing ecosystem changes (Sundy 2000; Moloney et al. 2011). Ocean acidification develops progressively without the kind of natural variability and oscillations we see in the development of the ocean climate [*Caldeira and Wickett*, 2003]

Most of the increase in global average temperature including ocean warming has been observed over the past 50 years (Figure 30-4), which contributes to sea level rise (SLR). The average global surface salinity change is not significant (-0.0024 ± 0.051), varying on gyre and basin scales with different evaporation/precipitation conditions [*Durack and Wijffels*, 2010]. The observed heat and salinity trends are also linked to changes in ocean circulation (Figure 30-4). Global warming and increased stratification of the ocean is very likely to drive lower levels of oxygen in the ocean, particularly in the ocean interior. There has been a substantial expansion of the oxygen minimum zones (OMZs) in the earth's tropical oceans over the past 50 years in all basins [*Stramma et al.*, 2008]. Dissolved oxygen level affects productivity, biogeochemical cycling and ecosystems in the ocean [*Keeling et al.*, 2010].

[INSERT FIGURE 30-4 HERE
Figure 30-4: (A) Changes in sea surface temperature (2010-2001 relative to 1948-1957); (B) time series of global ocean temperature above 220m relative to 1950–1999 average; (C) ocean salinity comparison of today versus 100 years of measurements; and (D) changes in sea level (2010 relative to 1993).]

The ocean absorbs about one third of the anthropogenic carbon dioxide emitted to the atmosphere each year [*Sabine et al.*, 2004]. The increasing CO_2 concentration in the ocean has driven ocean acidification [*Orr et al.*, 2005] at a rate faster than any other period seen for millions of years [*Caldeira and Wickett*, 2003; *Hoegh-Guldberg et al.*, 2007; *Pelejero et al.*, 2010; *Raven et al.*, 2005]. This change in ocean pH and chemistry (Figure 30-5a,b) has influenced ocean carbon storage (Figure 30-5c) and represents a major challenge for marine biogeochemical cycles and ecosystem processes, particularly calcification [*John M. Guinotte*, 2008]. Although research efforts to understand ocean acidification are growing, substantial evidence demonstrating acidification of the global ocean emerged after the release of AR4 [*IPCC*, 2007a; b; c]. Potential impacts of ocean acidification on marine organisms and biogeochemical cycles are complex and need to be considered with other environmental changes [*Doney et al.*, 2009; *John M. Guinotte*, 2008]. The understanding of adaptation and response of ecosystem to ocean acidification on regional and basin scales is very limited.

[INSERT FIGURE 30-5 HERE
Figure 30-5: (A) Ocean pH as a function of atmospheric CO_2 concentration; (B) aragonite saturation as a function of atmospheric CO_2 concentration; and (C) CO_2 flux and carbon storage as a function of atmospheric CO_2 concentrations (change relative to those at 280 ppm).]

30.3.1. Quality of Data Sets and Length of Time Series from the Ocean

The ocean is a complex environment that has only really been studied intently over the past 60 years, although some time series (e.g. the hydrographical time series from the northeastern North Atlantic, Klyashtorin and Lyubushin 2007). For this reason, it is important to consider the quality of data sets and their spatial and temporal variability. For surface water impacts, the time scale is immediate for sea level rise; and the ocean surface exchanges heat and CO_2 on an annual basis so that impacts of rising temperature and CO_2 on coral reef systems and coastal/upper ocean fisheries are felt today. In practice, the CO_2 signal precedes the thermal signal by some 30 years due to the lag time imposed by the heat capacity of the sea and land between the appearance of a greenhouse gas in the atmosphere and the full expression of its thermal signature [*Hansen et al.*, 1985] and at any time we have a significant degree of unrealized warming potential. But for the subsurface waters, time scales are far longer, and the temperature, O_2, and CO_2 signals may become decorrelated. The basis for observing the penetration of fossil fuel CO_2 into the ocean [*Brewer*, 1978] was established over 30 years ago and large-scale data sets are now available that reveal the signal with remarkable clarity [*Sabine et al.*, 2004]. Yet the penetration of heat into the ocean is observed with much greater difficulty due to the greater thermal noise in the climate system. Figure 30-4b illustrates the problem where the warming trend in the upper 220m of each ocean basin is identified, with short-term impacts of the cooling from volcanic eruptions displayed. This responsiveness contrasts with the trend within the bulk properties over huge ocean areas over a 50-year interval with a record of the penetration of fossil fuel CO_2 into the ocean, observable by much different means. In this case, the changing CO_2 status of the ocean is not extracted by a formula but is simply revealed in detail by direct comparison of repeat hydrographical sections at a 15-year interval [*Byrne et al.*, 2010].

The appearance of a non-anthropogenic changing CO_2 component at depth in only 15 years in the figure above raises questions. If were to attribute this to a climate related process we would have to invoke more rapid penetration of heat than CO_2, and a very high temperature sensitivity for deep-sea respiration changes. In practice, and as recognized by the authors, this is more likely a cautionary tale of the problem of observing a two-dimensional slice in a three dimensional ocean in motion. Small water mass displacements between the two intervals are the most likely explanation.

The profound differences in observing manner and signal recognition and resolution raise questions as to how well the combined impacts of temperature, oxygen, and CO_2 can be estimated in the sub surface ocean. In the atmosphere, the correlation between rising CO_2 levels and rising temperature has been carefully examined. No such correlation has yet been examined for the ocean but both signals are invading on the same time scales; we may then ask if an ocean correlation should be so. If this were true then the well resolved CO_2 signal might in some way serve as a proxy for heat; however it would seem to be unwise to expect this to be true except as a gross approximation. In practice the spatial patterns by which heat and CO_2 enter the ocean are not identical and there are ways in which an anti-correlation may occur. For example the ocean will take up CO_2 more effectively in the absence of warming, and cold events such those from volcanic emissions can lead to deeper winter time convection and increased CO_2 uptake. It is likely then but not proven that the observed passive CO_2 signal has penetrated deeper and more rapidly than its thermal counterpart with its buoyancy consequences.

The matter of the time and space scales over which a passive tracer such as CO_2 introduced to the ocean may be expected to reach equilibrium with the deep ocean has been examined by [*Wunsch and Heimbach*, 2008] and found to be long, complex, and dependent on source location. Although not strictly analogous to the problem investigated here the implication is that we cannot assume that the pattern of penetration of heat and CO_2 are well correlated, although this may be approximately so.

The problem of rising temperature and declining O_2 levels also presents problems in attribution and correlation with the invading CO_2 signal. In the upper waters of the ocean no time lags occur and impacts are more easily attributable. There the impact of rising temperature combines with O_2 stress to affect the thermal tolerance of fish species [*Pörtner and Knust*, 2007], and coral bleaching and mortality are now well established [*Hoegh-Guldberg*, 1999; *Hoegh-Guldberg and Jones*, 1999; *Jones et al.*, 1998], and there is now a substantial literature on the poleward migration of some coastal marine species [*Hoegh-Guldberg and Bruno*, 2010] Poloczanska et al. 2011)

For sub-surface waters the problem of declining O_2 levels is now raising concern on both an observational basis [*Chen et al.*, 1999; *Stramma et al.*, 2008; *Stramma et al.*, 2010]and through model calculations [*Shaffer et al.*, 2006]. But definitions of hypoxia differ widely, and some authorities (US Office of Science & Technology Policy, 2010) simply state that it is an empirically defined continuum with no specific physical attribution. This clearly poses a challenge for coupling predictions of change in the physical world to ecosystem impacts; it is very likely that understanding and prediction of this coupling can be improved.

It has long been the tradition in ocean science to report observed changes in O_2 consumption rates in the ocean as an exponentially declining function of depth [*Munk*, 1966; *Riley*, 1951; *Wyrtki*, 1962], and this tradition is carried through to model simulations of today [*Ito and Deutsch*, 2010; *Keeling et al.*, 2010; *Stramma et al.*, 2010]. In this way the temperature dependence of the decomposition rates, critical in a changing climate context, is included with other variables such as organic matter composition. Thus it is now a challenge to deconvolute these signals and reveal the actual temperature dependence of the system as is required here.

30.3.2. Influence of Multi-Decadal Climate Variability

Oceanic environments are also typified by multi-decadal climate variability over a range of frequencies from inter-annual to multi-decadal and over a range of amplitudes [*Trenberth and Shea*, 2006] and temporal scales of these phenomena are linked to specific spatial scales. Although there is no strong correlation between the temporal and spatial scales there is a general tendency that phenomena of larger spatial scales are linked to longer periods [*Dickey*, 1992]. For example, the length scale of the AMO, a measure of sea surface temperatures in the Atlantic, has periodicity from 50 – 70 years [*Sutton and Hodson*, 2005] and has a length scale of more than 10,000 km, while the length scale of the North Atlantic Oscillation (NAO), a sea level pressure index, has periodicity from 1 -10 years [*Hurrell et al*., 2004] and a length scale of about 1/3 of the AMO. Similarly, the North Pacific Index (NPI), a spatially-averaged sea level pressure index, has periodicity of 20 - 30 years [*Deser et al*., 2004] and typical length scale of 4 000 -5 000 km, while North Pacific Gyre Oscillation (NPGO), a sea surface level index, has periodicity of about 10 years and spatial scales of about half that of the NPI. These various climate modes have different origins and physical impacts, and they impact marine ecosystems in different ways. It also appears that many of them have opposite amplitude in the regions around their spatial extents as for the NAO [*Sundby and Drinkwater*, 2007; *van Loon and Rogers*, 1978] and for AMO [*Sutton and Hodson*, 2005].

Although the phenomena of longer periods have generally smaller amplitudes than the shorter-term periodicities, they appear to have larger impacts on marine ecosystems. This is because the persistence of the signal results in impacts over many life cycles and generations of the populations [*Sundby and Nakken*, 2008] and because the spatial scale is ocean wide and extends over many marine ecosystems. The shorter inter-annual climate variability, of most often much larger amplitudes, can have substantial impact on year-to-year recruitment variability and growth in fish stocks [*Cushing*, 1982] but such phenomena as separated single events are most often less influential on the long-term development in fish stocks and marine ecosystems unless they causes abrupt and irreversible (non-linear) responses. These latter kinds of responses are often the result of climate change amplified by other additional stressors such as overfishing which happened, for example, during the collapse of the Norwegian spring-spawning herring during the 1960s [*Toresen and Østvedt*, 2000] and with the collapse of the Northern cod in the late 1980s [*Rose et al*., 2000].

An important feature of the multi-decadal and large-scale climate phenomena is that their ecosystem impacts resemble those of anthropogenic climate change. Their rates of change have been larger than the anthropogenic climate change during the 20th century, but throughout the 21st century the predicted amplitude of anthropogenic climate change will substantially exceed the past observed amplitudes of multi-decadal natural climate variability. Past responses of the marine ecosystems can, therefore, give us some indication of how anthropogenic climate change during the 21st century will impact marine ecosystems of the global ocean, although extrapolation of the past observed impacts to the larger-amplitude future climate change should be considered with great care. The observed long-term changes in the marine ecosystems should also serve as validation and calibration for existing and future ecosystem models predicting impacts of climate change.

It should be noted that the observations of impacts on marine ecosystems from multi-decadal climate phenomena are largely limited to the North Pacific and North Atlantic Oceans, and within these areas most of the time series on ecosystems are limited to the northernmost parts. It has an advantage, since the largest temperature changes has taken place, and will occur from future climate change, in these areas [*IPCC*, 2007b] and they include the most productive parts of the oceans. However, the areas represent only northern high-latitude ecosystems, which cover a small fraction of the world’s oceans, and have ecosystems that function different than many other ocean regions. The areas range from temperate, through boreal, to arctic marine ecosystems in which spring-bloom dynamics dominate. In addition, there also exists some longer time series on ecosystem changes linked to some of the large upwelling areas. The advantage is that these are also high-productive areas, but they represent even smaller parts of the world’s oceans and, moreover, their ecosystem functioning is very specific.

The 20th century of the North Atlantic Ocean displayed a cold phase from 1900 to 1920s. Then the first warming occurred from 1920s to 1940s. The second cold phase occurred in the 1960s and 1970s, and the second warming started in the 1980s. The periodicity and the spatial scale of the phenomenon were described by [*Sutton and Hodson*, 2005]. Periodicity of 50-70 years was identified for the AMO on a longer time scale by tree ring analysis from Europe and North America back to the 1560s [*Gray et al*., 2004]. Changes in temperature from the cold phases to the warm ones during the 20th century were about 0.4°C on the spatially-averaged entire area of the North Atlantic, while in the northern region, e.g. Barents Sea, the change was 0.7°C. Most of these changes, both ups and downs, occurred within time intervals of 20 years.

Ecosystem impacts of the first warming phase from the 1920s to the 1940s was highlighted by the International Council for the Exploration of the Sea (ICES) during the early 1950s in an international symposium. [*Tåning*, 1953] described the northward movement of a number of fish stock in the northern North Atlantic. The Northeast Arctic cod, which has spawning areas along the Norwegian coast, had extended spawning areas as far north as Svalbard water in the Arctic during the early 1930s [*Iversen*, 1934]. [*Drinkwater*, 2006] made a comprehensive review of the ecosystem impacts during this first warming phase. It resulted in general northward movement of fish species both in the north-western and north-eastern Atlantic. All species, from warm-water species in the south, colder boreal species in the central areas, and arctic species in the northernmost areas were displaced northwards. The largest displacement occurred with the Greenland cod, which moved 1200 km northwards along the West Greenland coast, and changed the economy from a seal-dominated to a cod-dominated economy. Some warm-water species were occasionally observed even towards the northern boreal regions. Boreal species increased in total abundances, and Atlantic benthic species spread north-eastwards by about 500 km in the Barents Sea. Changes in the boreal parts of the region were assumed to be also linked to bottom-up effects as the abundance of zooplankton increased in West Greenland waters.

In the southern North Sea a change occurred in the entire ecosystem in benthos and the pelagic species from plankton to fish and sea birds during the 1920s to 1930s and shifted back again during the 1960s to 1970s. It was termed the “Russell Cycle”[*Southward*, 1980]. Although it was not at that time associated directly with multi-decadal climate variability, it was suggested that the changes could be a result of several factors such as fishing pressure, internal ecosystem changes and external “environmental factors” [*Cushing*, 1980; *Steele*, 1996]. However, it has been later directly associated with the multi-decadal climate variability in combination with other anthropogenic impacts as fishing and pollution [*Langmead et al.*, 2003].

The second warming phase from the 1980s to the present has been shown to have substantial impacts on the distribution of the zooplankton (specifically copepods) community [*Beaugrand et al.*, 2002]. The analysis was based on the extensive data series of the Sir Alistair Hardy Foundation (SAHFOS). Since 1958, many of the warm-water assemblages have moved up to 1000 km northward during the recent warming, and cold-water assemblages have retracted towards the Arctic. In addition to the above descriptions of ecosystem responses to parts of the AMO, there are two works describing responses to the full cycle throughout the 20th century. The spawning stock biomass of the boreal Norwegian spring-spawning herring in the Norwegian Sea-Barents Sea ecosystem has followed the multi-decadal climate variability from 2-4 million tons in the beginning of the 20th century to more than 16 mill. tons in the late 1940s [*Toresen and Østvedt*, 2000]. The subsequent collapse of the stock during the 1960s was caused by the combination of overfishing and a cooling climate. It was followed by a fishing moratorium for 17 years. The stock started the recovery parallel to the warming during the 1980s, and the stock has presently reached the same level of biomass as during the previous warm phase of the 1940s. Another boreal species, the Northeast Arctic cod, which spawns along the Norwegian coast and feeds in the Barents Sea, has shifted its spawning locals towards the northernmost fringes during the warm phases of AMO and shifted southward during the cold phases [*Sundby and Nakken*, 2008]. Along with the shifts in spawning locations, the biomass of the stock was higher during warm phases and lower during cold phases.

It appears that most of the ecosystem changes in response to AMO were reversible. In this regard, northward shifts during warming were followed by southward shifts during cooling and back again to northward shift during the second warming. However, there were also examples of irreversible responses such as for the West Greenland cod stock that boosted during the first warming from 1920s to 1940s, remained high during the subsequent cooling during the 1960s, but thereafter collapsed and did not recover again during the recent warming after the 1980s. Again, such irreversible changes seem to be associated with combined effects of climate and fishing pressure. There are fewer examples of how multi-decadal climate variability impacts ecosystems of the Pacific Ocean. [*Ito and Deutsch*, 2010] showed that along with the declining trend of oxygen concentration in the thermocline of the North Pacific there is a statistical significant spectral peak of 15-20 year periodicity. However, the mechanism connecting it to climate variability is uncertain.

30.3.3. Biological Responses

30.3.3.1. Global Trends

Although starting from a low base relative to the terrestrial literature [*Richardson and Poloczanska*, 2010; *Richardson and Poloczanska*, 2008], there has been an accelerating amount of literature which describes how a wide range of species, communities, and ecological processes are or are not responding to the changing environmental circumstances associated with climate change and ocean acidification (Hoegh-Guldberg and Bruno 2010; Poloczanska et al. 2011). Investigation of global patterns reveals changes in the distribution and abundance of species and communities, changes in ecosystem structure, and the loss of habitat forming species such as corals, kelp forests and mangroves [*Hoegh-Guldberg and Bruno*, 2010].

The warming of the upper layers of the ocean increases water column stratification, which reduces mixing, and the availability of nutrients to the sunlit upper layers of the ocean. Over the period from 1998 to 2006, the nutrient-poor "ocean deserts" of the Pacific and Atlantic Oceans have increased by 6.6 million km^2, or 15%, over the period 1998 to 2006 [*Polovina et al.*, 2008]. This observation is backed up by longer-term datasets such as that of [*Boyce et al.*, 2010] although significant debate continues regarding the assumptions relating Secchi Disc measurements of chlorophyll, which are seen by many as invalid. A recent analysis using satellite data by Signorini et al (2011) has revealed some differences between ocean basins, with significant trends being found in the Pacific and Indian oceans, but not in the north or south Atlantic (Figure 30-6, Table 30-1). How these changes relate to other areas of the ocean, is unclear, although the pattern is more complex for other areas and over longer timeframes [*Chavez*, 2011].

[Box on the intricacies of phytoplankton change in the ocean issue - Anthony Richardson to provide]

[INSERT FIGURE 30-6 HERE
Figure 30-6: Title? *[(a) monthly time series, (b) interannual variability plots, and (c) oligotrophic regions.]*]

[INSERT TABLE 30-1 HERE
Table 30-1: Linear trends of averaged Chl and Chl anomaly for all five gyres.]

Impacts of climate change on marine ecosystems across Earth's oceans have been systematically investigated by Poloczanska et al. (2011) who established a database of peer-reviewed literature to examine taxonomic, geographic and latitudinal trends of responses to climate change. Studies were selected using two criteria: (1) time series of observed changes after 1960, and (2) authors of studies who inferred or attempted to attribute observed effects to climate change. Using these criteria, observations were available for 31 broad taxonomic groups from primary producers to top predators, with 53 % of observations from bony fish and 17% from plankton. Data were taken from 238 marine studies published from 1991 onwards, with 57% of the studies published after 2006. Information extracted from the selected studies included location, the biological group concerned, quality and extent of attribution undertaken and whether the role of other driving factors such as exploitation or pollution were considered. Climate change responses were based on the authors' expectation for climate change impacts and therefore captured studies that appeared contrary to general expectations with climate warming, such as range shifts toward the equator driven by localised cooling in recent decades or later spring events linked to declines in sea ice. Observations were included that were consistent, opposite to expected (not consistent) or no change (not statistically significant). As attribution of responses to anthropogenic climate change involves correlation (and hence not necessarily causation), consideration was given to whether authors' inferred or discounted alternative explanations. The effect of publication bias, whereby scientists are more likely to report findings consistent with climate change in the literature, was reduced by repeating analyses only using data from publications that investigated multiple species.

At a global scale, impacts within the global ocean are widespread, with 74.4% of all observations (n=2006) highly consistent with climate change (Figure 30-7). Although observations are clustered in coastal waters and mid-latitudes of the Northern Hemisphere (Figure 30-7), they cover 45 of 54 large-scale oceanographic provinces [*Longhurst et al.*, 1995; *Longhurst*, 2007]. The majority of known ecological responses in the oceans are in distribution and abundance (Table 30-2) but also include changes in phenology calcification, community structure and demography.

[INSERT FIGURE 30-7 HERE
Figure 30-7: Consistent, opposite, no change, and unknown responses to climate change from marine studies.]

[INSERT TABLE 30-2 HERE
Table 30-2: Proportion of responses (%) consistent with climate change in each ocean region by observation type. Total number of observations given in brackets. ND= no data.]

Consistency across all ecological responses to climate change (Table 30-3) varies among taxonomic groups (Figure 30-8a). While the consistency with climate change varied among ecological responses, more than 50% of studies in each case were consistent with climate change (Figure 30-8b). Polar ecosystems appear to be most affected by climate change, with ~90% of responses consistent with climate change. Temperate, subtropical and tropical regions are significantly affected by climate change but with 70-75% of responses documented consistent with climate change (Figure 30-8c).

[INSERT TABLE 30-3 HERE
Table 30-3: Summary of first observations of species from the Atlantic Ocean where authors have suggested that climate change has played a role. Note that there are many instances of first observations in the literature but authors have not suggested possible reasons for the new observation and these particular papers have not been included here.]

[INSERT FIGURE 30-8 HERE
Figure 30-8: The proportion of biological responses consistent with climate change by (a) different taxa, (b) different types of response, and (c) latitudinal region. Means ± standard error are shown. Dashed vertical line represents a proportion consistent of 0.5, which indicates data are random. Solid vertical line represents the overall mean.]

Quantitative response can be measured for changes in distribution and phenology. The global average for distributional change is 49.2 ± 5.6 km per decade, and for phenology 4.9 ± 0.8 days per decade (Figure 30-9). Significant range shifts in the direction predicted by climate change occur in 7 of 9 taxonomic groups and are most pronounced for seabirds and copepods (Figure 30-9a). Similarly, a significant phenological response, consistent with climate change, occurred for 6 of 8 higher taxa, and the highest response occurred in turtles and bony fish (Figure 30-9b). Marine systems show faster phenological changes and far greater distributional changes than their terrestrial counterparts (Figure 30-9).

[INSERT FIGURE 30-9 HERE
Figure 30-9: A. Distribution (km.decade^{-1}) and B. phenology (days.decade^{-1}) changes for marine groups. Positive distribution changes are consistent with warming (generally poleward) and positive phenological changes are consistent with warming (generally earlier). Means ± standard error are shown. Dashed horizontal line is overall mean response.]

30.3.3.2. Regional Trends

The extent of climate change within the global ocean and much depends on which ocean basin is being examined. In order to understand the regional characteristics of climate change, we analysed the physical, chemical and biological trends within three ocean basins with the inclusion of a category embracing semi-enclosed Mediterranean seas, excluding polar seas (Figure 10).

- Atlantic Ocean and North Sea
- Pacific Ocean and Asian Seas
- Indian Ocean

- Mediterranean Sea, Red Sea, Arabian Gulf, Baltic Sea, American Mediterranean sea (Gulf of Mexico and Caribbean Sea) and the Australasian Mediterranean sea

[INSERT FIGURE 30-10 HERE
Figure 30-10: Regional oceans and seas. Left: Indian Ocean, middle: Atlantic Ocean and right: Pacific Ocean. Semi-enclosed Mediterranean seas 1: Red Sea, 2: Persian Gulf, 3: American Mediterranean sea (Gulf of Mexico and Caribbean Sea) 4: Baltic Sea, 5: (European) Mediterranean Sea 6: Australasian Mediterranean sea. *These images are from Wikipedia, I've drop shapes over the semi-enclosed seas*.]

30.3.3.2.1. Atlantic Ocean and North Sea

Physical and chemical changes

Although the Atlantic Ocean has warmed steadily over the past 50 years, the increase of SST is larger and faster in the North Atlantic than in the South Atlantic (Figure 30-4a). The pH of both the North and South Atlantic have decreased by around 0.1 pH units since the Industrial Revolution (Figure 30-5a) and has been accompanied by a general decrease in the Aragonite Saturation State (ASS) of around 0.5 (Figure 30-5b). The air to sea flux of anthropogenic carbon has been most prominent in the North Atlantic (rates up to 4.2 mol C m^{-2} y^{-1}) as opposed to the South Atlantic (rates up to 2.0 mol C m^{-2} y^{-1}). These changes have been accompanied by an increase in the water column anthropogenic carbon (which is greatest in the North Atlantic (increases of 60-210 mol C m^{-2}) versus the South Atlantic (increases of 30-60 mol C m^{-2}; Figure 30-5c).

The Atlantic Sea Surface Salinity (SSS, Figure 30-4d) showed an enhanced basin average salinity (0.078±0.095) in the 50 year data sets [*Durack and Wijffels*, 2010] Figure 30-4c). For example, the net evaporative North Atlantic has become saltier as a whole over the past 50 years [*Boyer et al.*, 2007; *Durack and Wijffels*, 2010]. Declining oxygen concentrations in the 200-700 m layer was recorded in the tropical Atlantic between 1960-1974 and 1990-2008, while some regions from 20N to 30N and from 30S to 20S showed increased oxygen content [*Stramma et al.*, 2008]. The hypoxic zone in the eastern South Atlantic expanded between the two time periods. Rates of sea level rise in the North Atlantic range from -5 to 5 mm y^{-1}, with the highest rates in the South Atlantic off the east coast of South America (up to 10 mm y^{-1}). Winds have generally increased across parts of the North and South Atlantic, although where storm systems have intensified is subject to debate. Comparing the last decade (2001-2010) to the period 1948-1957 reveals substantial changes in cloudiness.

Biological changes

A large number of biological systems within the Atlantic Ocean are undergoing changes that are consistent with climate change (overall 77.5% of 844 published observations). All types of biological responses were largely consistent with climate change (>50%) except for growth (28.6%), although there were only 6 growth observations. All calcification and demographic studies reported significant changes were consistent with climate change, while studies on the abundance of organisms showed lower rates of consistency with the directions expected under climate change (62.7% of 397 studies examined; Table 30-3). In some cases, changes within regions (e.g. the Caribbean Sea) interacted with more local scale stresses (Box 30-1). By contrast with other ocean basins, North and South Atlantic are not showing an increase in the size of the oligotrophic areas associated with their subtropical gyres even after the removal of the seasonal trends in the data sets (Figure 30-6).

_____ START BOX 30-1 HERE _____

Box 30-1 a scanned image; see first page of <WGIIAR5-Chap30_ZODfigs.pdf> or scroll to end of this file for the box graphics, which precede the chapter illustrations.

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Distribution and abundance

There is strong evidence that species are moving poleward in the Atlantic as waters warm, although almost all observations comes from the North Atlantic. These include 'warm-water' species that have been documented extending their poleward distribution edges toward the pole and 'cold-water' species that have retracted their southern more equatorial boundaries. Such species where climate change has been considered to be an important factor include hundreds of fish [*Brander et al.*, 2003; *Dufour et al.*, 2010; *Dulvy et al.*, 2008b; *Nye et al.*, 2009; *Perry et al.*, 2005; *van Hal et al.*, 2010], dozens of copepod species [*Beaugrand et al.*, 2009; *Beaugrand et al.*, 2002; *Bonnet et al.*, 2005; *Lindley and Daykin*, 2005], a cladoceran [*Johns et al.*, 2005], phytoplankton [*Hays et al.*, 2005], a coastal isopod [*Franke et al.*, 1998], sub-littoral benthic molluscs [*Beukema and Dekker*, 2005; *Beukema et al.*, 2009], a sandweed fly [*Edward et al.*, 2007], a neophyte [*Loebl et al.*, 2006], and barnacles [*Herbert et al.*, 2003; *Wethey and Woodin*, 2008]. Changes can also be complex. Some groups, such as sub-littoral benthic organisms, appear to be responding more slowly to changes in warming [*Hinz et al.*, 2011], although similar numbers of organisms responded in the expected and opposite direction under substantially warmer conditions in the English Channel over the past 50 years, suggesting a heterogeneous community response. For macroalgae off the Iberian peninsula, the 'warm-water' species showed predominantly a poleward shift in distribution but 'cold-water' species showed no retraction in their distribution [*Lima et al.*, 2007].

There is increasing evidence of the appearance of new species in areas that is likely to be a result of the movement poleward of species as waters warm (Table 30-2). Although new occurrence records are by themselves relatively weak, they help to provide evidence for the movement of the extreme poleward edge of distributions and thus a more complete picture of species movements. Table 30-2 suggests two main hotspots in the Atlantic. The first is off the Iberian peninsula, which is a boundary between subtropical and boreal species and where waters are warming rapidly. Here, climate change has been suggested to play a role in the movement poleward of a scleractinian coral [*López-González et al.*, 2010], the paper nautilus [*Guerra et al.*, 2002], a whale species [*González et al.*, 2000; *Guerra et al.*, 2002] and dozens of fish species [*Abecasis et al.*, 2009; *Acosta et al.*, 2009a; *Arronte et al.*, 2004; *Banon*, 2004; *Banon et al.*, 2002; *Guerra et al.*, 2002]; see Table 30-2). Another hotspot appears to be UK waters, a boundary between warm temperate and cold temperate species and where warming is happening rapidly. Nearly two dozen new fish species [*Byrkjedal et al.*, 2004; *Swaby and Potts*, 1999], a barnacle [*Southward*, 1995], a crab [*Dauvin*, 2009] and Cuvier's beaked whale [*Robinson and MacLeod*, 2009] have now been reported from UK waters.

As waters warm, there is the risk that new species that move into an area could be harmful or disruptive ecologically. There are a number of examples of this type of situation from the Northeast Atlantic shelf. Some species of harmful algal bloom such as *Prorocentrum* spp. and *Dinophysis* spp., which can produce okadaic acid that is stored in the tissue of shellfish that ingest the phytoplankton. This toxin causes diarrhetic shellfish poisoning in people eating contaminated oysters and mussels, leading to diarrhea, nausea, vomiting and cramps, although this is not fatal. Both *Dinophysis* spp. (DSP) and *Ceratium furca* have increased in numbers and spread their distribution in European shelf waters as waters have warmed [*Edwards et al.*, 2006]. An invasive species that is increasingly finding the warmer conditions of the European shelf more favourable is the comb jelly *Mnemiopsis leidyi*. This American ctenophore has some of the greatest ecosystem effects of all marine bioinvaders. *M. leidyi* was first recorded in the Black Sea in 1982, and was probably introduced via ballast discharge by ships from the east coast of the USA [*Shiganova*, 1998; *Shiganova and Malej*, 2009]. In combination with eutrophication and overfishing, this comb jelly reached biomasses estimated to be millions of tonnes and led to a total reorganization of the pelagic food web and significant economic losses, helping to virtually wipe out the anchovy fishery. This species is now found in estuaries along the Dutch coast [*Faasse and Bayha*, 2006] where it is likely to have been introduced by ballast water discharge of ships visiting busy Dutch ports. It is likely that warmer temperatures in the North Sea associated with climate change have allowed this species to survive and reproduce in the Dutch estuaries [*Faasse and Bayha*, 2006], as cold temperatures limit the distribution of this species[*Kremer*, 1994]. More recent invasions of the Baltic Sea and the Skagerrak have been hypothesized to originate from Dutch waters (Faasse & Bayha 2006). It is also possible that the now populations of *Mnemiopsis* in the southern North Sea estuaries may provide a constant supply of individuals in areas further north that are too cold currently for *Mnemiopsis* to survive the winter months.

One particular aspect of climate change is the potential for marine species to move between previously inaccessible ocean basins. A consequence of the retraction of the permanent sea ice in the Arctic Ocean is the likelihood of species spreading from the North Pacific to the North Atlantic Oceans[*Vermeij and Roopnarine*, 2008]. The Arctic Ocean has been ice covered for most of the past 14 million years, except during the warm mid-Pliocene epoch around 3.5 million years ago. As currents in the Bering Sea are northward as they are today, many North Pacific taxa (particularly mollusks) were transported into the Arctic Ocean. Conditions in the Arctic were then sufficiently warm to enable survival of temperate organisms. As the Arctic ice sheet contracts now, prevailing winds in the region push Pacific water along the North American Arctic continental shelf in an eastward direction and through the Canadian Archipelago [*Dickson*, 1999; *Jones et al*., 2003]. This opens up the equivalent of an expressway between the North Pacific and North Atlantic Oceans which could potentially allow hundreds of marine lineages to colonise the Arctic and North Atlantic Oceans [*Vermeij and Roopnarine*, 2008]. There is evidence that this is already happening. Climate models and observed trends from satellite showing contraction and thinning of Arctic sea ice predict seasonal or permanently ice-free conditions in the nearshore Arctic Ocean by 2050 [*Wang and Overland*, 2009]. However, the fingerprint of North Pacific surface water (relatively brackish, with a high ratio of silicate and phosphate to nitrate) being transported into the Northwest Atlantic is already evident [*Jones et al*., 2003]. At least one planktonic organism has moved from the North Pacific Ocean to the North Atlantic Ocean. The marine diatom, *Neodenticula seminae*, is found in large numbers in the polar North Pacific Ocean. Paleo-records indicate that it was last found in the North Atlantic Ocean 800,000 years ago [*Reid et al*., 2007]. It was first reported again in the North Atlantic in 1999 from the Labrador Sea and has spread east since to almost Iceland [*Reid et al*., 2007]. It is highly likely that this diatom was transported from the North Pacific to the North Atlantic via the Arctic Expressway when the sea ice was at a minimum in 1998. This event could be an indicator of the scale and speed of future changes in the Arctic and North Atlantic oceans as oceans warm. The increased volume of Pacific water entering the North Atlantic will also have profound impacts on the phytoplankton community, with concentrations of silicate three times as high in the Pacific than in the Atlantic Ocean.

There is some, albeit limited, evidence that some marine species are moving deeper in the water column as waters are warming. This is the marine analogue of species moving upward on land as climate is warming. There are only two marine studies of changes in depth distribution with climate and both are for fish. [*Dulvy et al*., 2008a] analysed annual changes in the depth distribution of 28 demersal fish species from fish monitoring surveys from 1980-2004 in the North Sea. European shelf waters are warming faster than the global average, with a 1·6°C increase in bottom temperatures over the 25-year study period. The entire demersal fish assemblage moved 3.6 m per decade deeper in the water column and was significantly related to winter bottom temperature. A total of 22 of the 28 individual fish species moved deeper in the water column. Importantly, demersal fish showed stronger and more coherent movement deeper in the water column than horizontal distribution shifts with warming, highlighting the need to investigate multiple aspects of a species response to climate change to develop a more realistic picture. The other marine study on changes in depth distribution is from the NW Atlantic. [*Nye et al*., 2009] described changes in the mean depth distribution of 36 fish species off the NE USA continental shelf was assessed using data from annual spring trawl surveys from 1968-2007. In terms of depth distribution changes, they found that 3 opposite, 17 expected and 16 no change. Interestingly, stocks in the southern extent of the survey area exhibited much greater poleward shifts in center of biomass but only some moved deeper. However, in the northern area in the Gulf of Maine, there were minimal changes in the center of biomass were observed in stocks, but mean depth of these stocks increased. Other marine species might be behaving similarly and shifting their distributions deeper in the water column but presently there is insufficient information. Further work is needed on depth distribution changes in marine organisms, and trawls from research cruises provide an extensive dataset with which to do so.

Shifts in phenology

Phenology, or the timing of repeated seasonal activities such as migrations or reproduction, is highly sensitive to global warming. On land, events in spring, including the arrival of swallows in the UK, the emergence of butterflies in the US, or the blossoming of cherry trees in Japan, are all happening earlier in the year as the temperature rises [*Parmesan and Yohe*, 2003]. Although there have been far fewer studies of phenology in the oceans, the accumulating evidence suggests similar changes in timing are happening in the ocean compared with that of land Poloczanska et al. (2011).

Studies for changes in phenology in the Atlantic in relation to climate change have only been published from the North Atlantic, and most of the observations are from the Northeast Atlantic, particularly the North Sea. Phenological changes toward earlier appearance as conditions warm have been observed across the foodweb, including phytoplankton [*Edwards et al.*, 2006; *Schluter et al.*, 2010; *Wiltshire and Manly*, 2004], zooplankton [*Costello et al.*, 2006; *Edwards et al.*, 2006; *Greve et al.*, 1996; *Greve et al.*, 2004; *Reid et al.*, 1998], intertidal organisms [*Beukema et al.*, 2009; *Moore*, 2010; *Philippart et al.*, 2003], fish [*Dufour et al.*, 2010; *Juanes et al.*, 2004; *Kennedy and Crozier*, 2010; *Teal et al.*, 2008], seabirds [*Frederiksen et al.*, 2004; *Moller et al.*, 2006; *Votier et al.*, 2009; *Wanless et al.*, 2009] and turtles [*Hawkes et al.*, 2007; *Pike et al.*, 2006; *Weishampel et al.*, 2004].

A critical aspect of phenological change in the ocean is the timing of spring and autumn blooms in relation to warming in highly productivity temperate regions. This is important because the most obvious and widespread timing changes on land have been in spring. In the North Sea, there has been no general advancement (or delay) in the timing of spring or autumn from 1958-2002[*Edwards and Richardson*, 2004]. Although the timing of the spring bloom is often considered to be determined by the onset of stratification, this is not a prerequisite (Townsend et al., 1992) and, in many areas, may instead be more tightly coupled with the regulation of diatom spore germination by photoperiod [*Eilertsen and Wyatt*, 2000; *Eilertsen et al.*, 1995], which is invariant to global warming.

There is evidence from the NE Atlantic that predator–prey mismatches that could resonate to higher trophic levels [*Edwards and Richardson*, 2004; *Greve et al.*, 2004]. The timing of various plankton functional groups seems not to respond to ocean warming synchronously. Over the summer stratified period from 1958 to 2002, dinoflagellates in the North Sea peaked earlier by 23 days, diatoms by 22 days, copepods by 10 days, and other holozooplankton by 10 days. This differential response of phytoplankton and zooplankton could lead to a mismatch between successive trophic levels and a change in the synchrony between primary, secondary, and tertiary production. Efficient transfer of marine primary and secondary production to higher trophic levels, such as those occupied by commercial fish species, depends largely on the temporal synchrony between successive trophic production peaks, especially in temperate marine systems. Here, successful fish recruitment is highly dependent on synchronization with pulsed planktonic production [*Beaugrand and Reid*, 2003; *Beaugrand et al.*, 2003; *Cushing*, 1990; *Hjort*, 1914]. This type of mismatch, where warming has disturbed the temporal synchrony between the dynamics of herbivores and their food, has also been noted in freshwater [*Winder and Schindler*, 2004], estuarine [*Costello et al.*, 2006], and terrestrial ecosystems [*Visser and Both*, 2005].

Demographic changes, changing community structure, condition

Changes in the demographic characteristics of a range of organisms have been reported, particularly for seabirds whose populations have decreased rapidly in species such as the Black-legged kittiwake [*Frederiksen et al.*, 2007], the Northern Fulmar [*Grosbois and Thompson*, 2005; *Lewis et al.*, 2009], and the Common Murre [*Votier et al.*, 2008]. Other organisms that have shown changes in demographics include the intertidal Black-footed and common limpet species [*Moore et al.*, 2011], subtidal bivalves [*Philippart et al.*, 2003], sea turtles [*Hawkes et al.*, 2007] and a number of fish species from the NE US and Canada [*Collie et al.*, 2008]. Changes in community structure has been seen in fish [*Benoit and Swain*, 2008; *Collie et al.*, 2008; *Genner et al.*, 2010; *Henderson*, 2007; *Henderson and Bird*, 2010; *Hiddink and ter Hofstede*, 2008], intertidal [*Hawkins*, 2008; *Smith et al.*, 2006; *Warwick and Turk*, 2002] and plankton communities [*Beaugrand and Reid*, 2003; *Beaugrand et al.*, 2009; *Kirby et al.*, 2009; *Wiltshire et al.*, 2010].

Growth and condition can be positively or negatively affected by global warming. For example, warming in the NE Atlantic from 1992-2006 has led to poorer feeding conditions for salmon that return to European streams [*Todd et al.*, 2008]. The condition of winter adults at freshwater re-entry was negatively related to sea surface temperature experienced at sea. The poorest condition fish had very low lipid stores that compromise spawning success. The warm conditions in the NE Atlantic have led to lower biomass and smaller zooplankton [*Beaugrand and Reid*, 2003] that are likely to provide poorer food conditions for salmon whilst at sea. However, warmer temperatures can also enhance growth rate. Data from the SE North Sea from 1970-2004 show an increase in growth rate for sole, a warm-water species that spawns in spring, and a much smaller increase in for plaice, a temperate species that spawns in winter [*Teal et al*., 2008]. The authors conclude the further warming is likely to positively influence sole but detrimentally affect plaice.

Calcification

There are only two studies that have shown observed changes in the calcification in the Atlantic Ocean. Although calcification is considered to negatively affect most calcifying organisms, recent work by [*Iglesias-Rodriguez et al*., 2008] has shown that coccolithophores, which contribute about 1/3 of total marine calcium carbonate production, could be stimulated by ocean acidification since the Industrial Revolution and could continue to do so. In the laboratory, particular inorganic and particulate organic carbon and their production rates increased. Coccolith volume also increased from 300 to 600 ppmv. This was mirrored from field evidence from a location in the sub-polar North Atlantic southwest of Iceland, where over the past 220 years there has been a 40% increase in average coccolithophore mass. Larger coccolith species at the site showed an increase in lith (skeletal) mass, but smaller species showed a possible decline in lith mass [*Halloran et al*., 2008].

30.3.3.2.2. Pacific Ocean and Asian Seas

Physical and chemical changes

The Pacific Ocean consists of half the ocean area and one-third of the earth's surface. It deserves a special focus as the largest single geographic feature on our planet, the Pacific Ocean harbors a major proportion of the earth's biodiversity and hundreds of millions of people. Overall, the warming and freshening over the upper Pacific Ocean was reported, but parts of the North Pacific and equatorial Pacific have cooled over the past 50 years (Figure 30-4b), e.g., warming in the North Pacific subtropics, cooling around 40N° and slight warming farther north is the pattern associated with a positive PDO [*IPCC*, 2007b]. A cooling in Eastern Pacific upwelling areas (e.g. The California Current and Humboldt Current) was observed recently [*Belkin*, 2009] and is evident in Figure 30-4a. A basin averaged freshening in the Pacific Ocean (-0.044±0.064 psu) was observed in last 50 years [*Durack and Wijffels*, 2010]. Regional changes of salinity in the Pacific showed the spatial variation of the balance of precipitation and evaporation. Sea surface salinity in the tropical Pacific has declined in the precipitation-dominated western equatorial regions and in the South Pacific Convergence Zone in 50 years, while surface salinity has increased in the evaporation-dominated zones in the southeastern and north-central tropical Pacific [*Cravatte et al*., 2009]. The fresh, low density waters in the warm pool of the western equatorial Pacific have expanded significantly accordingly [*Cravatte et al*., 2009; *Delcroix et al*., 2007]. In the North Pacific, the subtropical thermocline has freshened since the early 1990s, following surface freshening that began around 1984 [*Riser et al*., 2008]; the freshening extends down through the intermediate water [*Nakano et al*., 2007]. Similarly, sea level changes vary greatly geographically (Figure 30-4d). The observed data indicate that high rates of sea-level rise over the western Pacific (approaching 30 mm yr^{-1}) and sea-level falls in the eastern Pacific (approaching −10 mm yr^{-1}) for 1993 to 2001 [*Church et al*., 2006]. The non-uniform sea level changes in South China Sea have also been observed during the same period [*Cheng and Qi*, 2007; *Li et al*., 2002].

The direct observation of surface water pH at a long-term time-series in the central North Pacific Ocean (Hawaii Ocean Time series, HOTs) showed an annual decrease of -0.0019±0.0002 from 1988 to 2007 (Figure 30-11, [*Dore et al*., 2009]). This confirms the overall projections from Figure 30-5a, which were calculated from atmospheric CO_2, total alkalinity, temperature and other parameters [*Cao and Caldeira*, 2008]. Variable long-term pH trends were observed for subsurface layer. In the subsurface strata, influenced by remote water mass formation and intrusion and biological carbon remineralization, enhanced acidification was recorded. The other basin-wide direct measurement in North Pacific showed significant pH change in the upper 500 m between 1991 and 2006 [*Byrne et al*., 2010]. The upward migration of the aragonite saturation horizons due to anthropogenic CO_2 uptake is currently 1-2 m year^{-1} in the North Pacific [*Fabry et al*., 2008]. A decadal increase of DIC inventory in Pacific Ocean was observed by [*Sabine et al*., 2008]. Between 1994 and 2004, the average increase of anthropogenic CO_2 inventory along 30°N of Pacific was 0.43 mol m^{-2} a^{-1}, which is also depicted in Figure 30-5c. Along 152°W of Pacific, the value was 0.25 mol m^{-2} a^{-1} between 1991/1992 and 2006 in Northern Hemisphere and 0.41 mol m^{-2} a^{-1} between 1991 and 2005 in Southern Hemisphere [*Sabine et al*., 2008]. In coastal areas, the 8-year record from coastal east North Pacific Ocean (Tatoosh Island) showed a rapid pH decline as well [*Wootton et al*., 2008]. Furthermore, it was suggested that anthropogenic CO_2 and seasonal upwelling contributed together to the serious acidification occurred along continental shelf of east North Pacific Ocean [*Feely et al*., 2008].

[INSERT FIGURE 30-11 HERE
Figure 30-11: Time series of mean carbonic acid system measurements within selected depth layers at Station ALOHA, 1988-2007 (Dore et al., 2009).]

In the open ocean areas of the Pacific, the declining of O_2 concentration in the water column occurred horizontally and vertically, expending OMZs. A substantial vertical expansion and intensification of the intermediate-depth OMZs in the equatorial Pacific Ocean during the last 50 years was observed (Fig. 12; [*Stramma et al*., 2008; *Stramma et al*., 2010]. A westward expansion of hypoxic zone in the equatorial Pacific was observed between 1960-1974 and 1990-2008 [*Stramma et al*., 2008]. The oxygen decrease in the 300- to 700-m layer was 0.13-0.32 mmol kg^{-1} yr^{-1} and the integrated oxygen loss was 49-74 mmol m^{2} yr^{-1}. More serious declining oxygen level was recorded in the North Pacific (Fig. 13; Whitney et al., 2007). In the interior water of 100-400m, oxygen was declining at 0.39-0.70 mmol m^{2} yr^{-1} or at an integrated rate of 123 mmol m^{-2} yr^{-1} during last 50 years. Meanwhile, the hyposic boundary (defined as 60 mmol O_2 kg^{-1}) has shoaled from -400 to 300m. Similar phenomena were observed at East Pacific Ocean over the period 1984-2006 (Bograd et al., 2008). Intense declines of dissolved oxygen (up to 2.1 mmol kg^{-1} yr^{-1}) occurred in the southern California Current System and the largest decline was below the thermocline. The hypoxic boundary has shoaled by up to 90m at the southern California Current System. The open Pacific Ocean oxygen decrease might also contribute to hypoxic condition in coastal area of North America [*Chan et al*., 2008].

[INSERT FIGURE 30-12 HERE
Figure 30-12: (A) Climatological mean dissolved oxygen concentrations at 400m depth …. (Stramma et al., 2008); and (B) dissolved oxygen concentration maps vs. time (1960-2008) and pressure ….]

[INSERT FIGURE 30-13 HERE
Figure 30-13: Temperature and oxygen trends at Ocean Station P on the 26.5 (×), 26.7 (◊), 26.9 (+) and 27.0 (□) isopycnal surfaces and at station P4 on the 26.7 surface. T and oxygen trends from linear regressions are provided in Table 1. Depth ranges (average and standard deviation) are 140 ± 15 m, 168 ± 17 m, 278 ± 27 m and 370 ± 44 m on the 26.5, 26.7, 26.9 and 27.0 isopycnals, respectively. P4 is warming at 0.0084 °C y−1, with O2 declining at 1.22 μmol kg−1 y−1. Two mesoscale eddies are labelled 1 and 2. Source: Whitney et al. (2007).]

The warming in the Pacific Ocean is very likely attributed to the anthropogenic climate change. However, it is still unclear that if anthropogenic climate warming has an impact on tropical cyclone activity. Under the global warming, future tropical cyclones (typhoons and hurricanes) will become more intense but the tendency of tropical cyclone activity in the western North Pacific and Atlantic are still controversial [*Emanuel*, 2005 ; *Emanuel et al*., 2008; *Knutson et al*., 2010; *Landsea et al*., 2010; *Landsea et al*., 2006; *Webster et al*., 2005] The surface salinity of the tropical Pacific Ocean has been declining although surface salinity has increased in the North East and North Central tropical Pacific where evaporation dominates (Ch3, WG1). The mixed layer of the tropical North Pacific has become less saline since early 1990s.

Biological changes

A large proportion of published studies from the Pacific reported changes (70.2% of 533 total observations) that were consistent with the direction climate change (Figure 30-7). Most observations occurred with respect to changes in the distribution and abundance of sea birds, foraminifera, and bony fish (Table 30-2, Figure 30-14c). The majority of evidence comes from the relatively well-studied Northern Pacific with the data for the Southern Pacific overwhelming from the Australian region.

[INSERT FIGURE 30-14 HERE
Figure 30-14: (A) and (b) observations for Pacific Ocean, and (C) proportion of observations (%) consistent with climate change by taxa. Number of observations given in brackets. ND = no data. Only taxa groups with >5 observations shown. *anemones and corals.]

Distribution and abundance

Evidence is emerging of changes in distribution and abundance in all regions of the Pacific. In the western Pacific marginal seas, observations recorded of expansion of a tropical seagrass into Korean coastal waters [*Kim et al.*, 2009], increase in abundance and expansion of decapods in Changjiang estuary, China, and an expansion of tropical corals into temperate Japanese seas [*Yamano et al.*, 2011].

In south-western waters, a strengthening of the East Australian Current is resulting in a shift in polewards shift climatology of around 350km and dramatic changes in biodiversity of western Tasman Sea [*Johnson et al.*, 2011; *Ridgway and Hill*, 2009]. Southern range extensions observed in eastern Tasmanian waters in several species of fish [*Last et al.*, 2011], invertebrates [*Johnson et al.*, 2011; *Pitt et al.*, 2010]**,** the invasive European shore crab *Carcinus maenas [Thresher et al., 2003]*, the sea urchin *Centrostephanus rodgersii* [*Ling*, 2008; *Ling et al.*, 2009a; *Ling et al.*, 2009b] and dinoflagellates [*Hallegraeff*, 2010] have been ascribed to enhanced transport of larvae and juveniles in the stronger East Australian Current and regional warming. 45 species of coastal fish from 27 families (about 30% of the inshore fish families occurring in the region) exhibited polewards shifts in distributions or increased abundance in Tasmanian waters comparing present day information (1995-2009) to the 1980s (1970-85)[*Last et al.*, 2011]. In contrast, a study of animal (fishes, benthic invertebrates) and plant communities (macroalgae) at 136 rocky reef sites around Tasmania found no significant changes on communities when census data from 1992-1995 was compared with 2006-2007 [*Stuart-Smith et al.*, 2010]. However, the study may have encompassed a relatively stable period following an abrupt change. The urchin *Centrostephanus rodgersii* has spread from mainland Australia to Tasmania in 1978 and subsequently increased both range and abundance and is now the dominant invertebrate on shallow subtidal rocky reefs over much of eastern Tasmania [*Johnson et al.*, 2011]. The strengthening of the East Australian current has improved climatic suitability of novel habitat for *C. rodgersii* and provided the supply of recruits necessary for colonisation [*Banks et al.*, 2010]. Overgrazing of macrolagae (kelp beds) by *C. rodgersii* has led to the formation of 'urchin barrens' with considerable loss of biodiversity [*Johnson et al.*, 2011; *Ling*, 2008].

In the Californian Current system dramatic changes have also been observed with changes in the abundance of seabird species at sea, pteropods and forms consistent with climate change[*Hyrenbach and Veit*, 2003; *Ohman et al.*, 2009; *Sydeman et al.*, 2001]. Retrospective analysis for foraminfera from sediments of the Californian Current reveal an increase in sub-tropical species and a decrease in temperature/sub-polar species over the 20th century consistent with warming [*Field et al.*, 2006]. Analysis of 50- year larval fish time series from the California Cooperative Oceanic Fisheries Investigations indicated that exploited species show a much clearer distributional response to climate alteration than unexploited [*Hsieh et al.*, 2008]. Further, analysis of long term trends in larval fish of 309 taxa in the southern Californian Current indicated unexploited species track climate trends more closely the exploited species [*Hsieh et al.*, 2005] Lee et al 2009, Tian et al. 2006]

Shifts in phenology

Phenological observations are of the timing of peak biomass of copepods and reproductive parameters in seabirds in the Northern Pacific with the addition of observations from little penguin colonies *Eudyptula minor* south-west Pacific. Reproductive parameters in seabirds tend to reflect food availability in the same season. Egg laying date (-ve), chick mass (+ve) and number of chicks fledged per pair (+ve) of *E. minor* in southern Australia were all correlated (1968-2007) with late-summer sea surface temperatures [*Cullen et al.*, 2009]. There has been a trend towards later mean laying date (6.5 days dec^{-1}) however, models project that this trend will be reversed in the near future as sea surface temperatures warm and colony productivity should improve [*Cullen et al.*, 2009].
For the Northern Pacific, phenological responses linked to climate change have been observed for seabird reproduction in British Columbia and the Gulf of Alaska [*Bertram et al.*, 2001; *Gaston and Smith*, 2001; *Gjerdrum*

et al., 2003] and Californian Current [*Sydeman et al.*, 2009]. Copepod biomass has been increasing in the far north with the peak appearance in Vancouver and Alaska region of the northern Californian Current being the earliest ever recorded over 2003-2006 [*Bograd et al.*, 2010] Decadal trends towards earlier spring (advancing phenology) have been observed in temperature, copepod peak biomass and seabird (3 species of piscivorous alcids) reproduction at Triangle Island, British Columbia since the mid 1970s [*Bertram et al.*, 2001; *Mackas et al.*, 1998]. Water temperatures have increased from the lowest temperatures on record in 1971 to some of the highest values ever observed in the 1980s and particularly in the 1990s, although 1999 was very low [*Bertram et al.*, 2001]. Peak biomass of copepods advanced 13-22 days dec^{-1} [*Bertram et al.*, 2001; *Mackas et al.*, 1998] >ean hatch dates of piscivorous Rhinoceros auklet *Cerorhina monocerata*, Tufted puffin *Fratercula cirrhata* and Common murre *Uria aalge* advanced 6-24 days dec^{-1} [*Bertram et al.*, 2001] [*Gjerdrum et al.*, 2003]. In contrast, no trend and high variability was observed in mean hatch date of the planktivorous Cassin's auklet *Ptychoramphus aleuticus*. It was proposed that warm spring leads to a mismatch between copepod availability and predator populations.

Demographic changes, changing community structure, condition

In the California Current ecosystem, seabird reproductive phenology, and productivity have changed in ways consistent with predictions under climate change but low-frequency may explain some of the patterns [*Sydeman et al.*, 2009]. The California Current is a complex ecosystem with the south composed mostly of sub-tropical species and the north of sub-arctic species [*Sydeman et al.*, 2009]. The California Current Ecosystem responds to interannual climate variability exemplified by El Nino-Southern Oscillation and long-term variability exemplified by Pacific Decadal Oscillation and North Pacific Oscillation Gyre [*Sydeman et al.*, 2009].[*Bograd et al.*, 2010]. There have been dramatic changes in seabird phenology in recent years influenced by coastal upwelling [*Bograd et al.*, 2010]. Mean egg laying dates of common Uria has become earlier over time, sub-artic species have become rarer in the southern California Current , the southern seabird community has become less abundant and less diverse while in the northern Californian Current, the community has become more abundant and more diverse and productivity of species have altered [*Sydeman et al.*, 2009]. Changes in productivity of auklets and murres were related to changes of prey (copepods and forage fish) biomass [*Sydeman et al.*, 2009].

Calcification

Evidence is emerging of declining calcification of massive corals on the Great Barrier Reef in the south-west Pacific linked to warming temperatures and declining pH. Skeletal density, annual extension and calcification have declined by 3.6%, 10.2% and 12.9% dec^{-1} respectively for *Porites* sp [*Cooper et al.*, 2008]. Further evidence of declines in growth rates are emerging for corals in Thailand as well as the Caribbean and Panama (get refs). [*De'ath et al.*, 2009] analyzed rates over 1900-2005 from *Porites* cores from 328 colonies on the Great Barrier Reef and for a sub-set of 10 colonies, extended observations back to 1572. Calcification rates have declined by 21% in recent decades in two regions of the Great Barrier Reef 450km apart – a decline unprecedented in the longer observations.

30.3.3.2.3. Indian Ocean

Physical and chemical changes

The Indian Ocean has been warming steadily over the past 50 years, with the greatest changes occurring in the Southern sections of the ocean [*Alory et al.*, 2007; *Ihara et al.*, 2008; *Levitus et al.*, 2009]. Rates of increase are highest in the southern portion of the Indian Ocean. However, compared to the other two oceans, the warming in the Indian Ocean and Australian–Indonesian seas is slow [*Alory et al.*, 2007; *Belkin*, 2009; *Levitus et al.*, 2005; *Levitus et al.*, 2009]. Basin averages of salinity in surface Indian Ocean was a near-neutral result (-0.001±0.061). Salinity has been declining within the net precipitation regions of the Bay of Bengal and the warm pool. In contrast, the salinity of the Arabian Sea, Western and Southern Indian Ocean have been increasing [*Durack and Wijffels*, 2010]. Warming and freshening of abyssal waters in the eastern Indian Ocean between 1994/95 and 2007 are quantified [*Johnson et al.*, 2008]. Both warming and freshening reduce the density of seawater, contributing to the vertical expansion of the water column [*Domingues et al.*, 2008]. The changes below 3000 dbar in these basins suggest local contributions approaching 1 and 4 cm of sea level rise, respectively [*Johnson et al.*, 2008].. Changes in sea level are greatest in the central and western portion of the Indian Ocean. As will other oceans, pH and the concentration of carbonate ions are steadily decreasing.

The pH and aragonite saturation levels of the Indian Ocean show similar trends to those of the other ocean basins (Figure 30-5a,b), with a steady erosion occurring as CO_2 increasingly penetrates the upper layers of the Indian ocean. Sea level rise is highest in the southern parts of the Indian Ocean (Figure 30-4d). Most regions of the tropical Indian Ocean showed decreased oxygen content in 200-700 m waters. The hypoxic zone in the tropical eastern Indian Ocean expended [*Stramma et al.*, 2008; *Stramma et al.*, 2010]. Intensified anoxia was reported on the Indian continental shelf (e.g. the Arabian Sea and Bay of Bengal) as well [*Paulmier and Ruiz-Pino*, 2009].

Biological changes

The number of published studies on biological changes occurring within the Indian Ocean is substantially less than that associated with the Pacific and Atlantic oceans, and the semi-enclosed seas. Less than 10 observations occur in each category with no observations for phenology and community change (Table 30-2) Where observations were recorded, between 42.8% and 100% of responses published were in directions consistent with the impacts of climate change depending on the observation type. In this respect, consistent changes have been reported in distribution and abundance of species, calcification rate, condition and demography, (Table 30-2). Long-term observations (>10 yrs) generally come from the southern Indian Ocean and are of seabirds at breeding colonies and at sea. Marked seasonality in the north Indian ocean driven by monsoonal dynamics, which coupled with heavy exploitation rates and limited monitoring may be masking long-term trends.

Distribution and abundance

The consistency in changes to the distribution and abundance, and similarity in timing observed across several seabird colonies in south Africa from 1990s to mid-2000s, suggest a role of climate forcing at large scales although alteration of prey populations or fisheries impacts may account for some observed changes [*Crawford et al.*, 2008]. Southwards expansion in seabird colonies in southeast Indian Ocean have also been observed (Dunlop) and in the summer at-sea distributions of 12 species of Albatross and Petrels [*Péron et al.*, 2010]. In all these studies, changing climate was considered to have had a significant effect, although species-specific responses highlight susceptibility is influenced by seasonal mortality, migratory traits, water mass affinities and fisheries.

Shifts in phenology

No studies have focused on shifts in phenology were found.

Changes in community structure, demography, and condition

Information on changes in community structure, demography and condition were limited to a total of 4 studies.

Calcification

Analysis of shell weight of planktonic formanifera *Globigerinoides ruber* in western Arabian Sea sediments found younger shells were lighter with thinner walls [*de Moel et al.*, 2009],. However, sediment trap samples show that lighter shells are also produced during monsoonal upwelling (when CO_2-rich deep water is bought to the surface). Seasonality alone cannot explain the patterns in shell weights from sediment samples implying anthropogenic ocean acidification is acting on top of the seasonal influences.

30.3.3.2.4. Semi-enclosed seas: Mediterranean Sea, Red Sea, Arabian Gulf, Baltic Sea, American Mediterranean sea (Gulf of Mexico and Caribbean Sea) and the Australasian Mediterranean sea

Physical and chemical changes

Compared to open ocean, the semi-enclosed mediterranean seas undergo relatively fast warming [*Belkin*, 2009]. Water exchange with the open ocean is limited and circulation is dominated by salinity and temperature gradients. Various long-term time series sea surface temperature data sets (1982-2006) showed rapid increase in Baltic, Mediterranean and other European Seas and in the Red Sea of the Indian Ocean at rates several times the global rate [*Belkin*, 2009]. Warming is slower in the Caribbean and Gulf of Mexico with the Australasian Mediterranean sea showing one of the slowest warming rates of the semi-enclosed seas.

Regime shifts encompassing a multitude of physical properties and ecosystem variables have been found in the north-east Atlantic during and its marginal and semi-enclosed seas (North Sea, Baltic Sea, Wadden, Balck Sea and Mediterranean) during the late 1980s. Analysis of records for the Mediterranean point to a regime shift in the late 1980s with marked changes in circulation [*Conversi et al.*, 2010]. The Eastern Mediterranean Transit (EMT), modification of Mediterranean deep water formation, is a phenomenon that started at the end of the 1980s, but has relaxed since the end of the 1990s that affected thermohaline and bio-geochemical properties of Mediterranean waters [*Conversi et al.*, 2010].

Biological changes

Studies undertaken within semi-enclosed seas revealed high consistency with climate change with 93.0% of a total of 174 published observations showing consistency with the expected direction under climate change Figure 30-2c). Consistency was 93% for abundance (n=43), 94.9% for distribution (n=117) and 100% for phenology (n=12). The majority of observational evidence is from the well-studied Mediterranean and Caribbean Seas.

[INSERT FIGURE 30-15 HERE
Figure 30-15: (A) and (B) observations for Mediterranean and Caribbean, and (C) proportion of observations (%) consistent with climate change by taxa. Number of observations given in brackets. ND = no data. Only taxa groups with >5 observations shown. *mysids and crabs]

Distribution and abundance

The Mediterranean marine biodiversity is undergoing rapid 'tropicalisation' [*Bianchi*, 2007; *CIESM*, 2008]. The Mediterranean has a long history of warm-water exotic species introduced by humans (generally by mariculture and shipping) and also naturally by the encroachment of sub-tropical Atlantic species through the narrow Straits of [*Galil*, 2008]. Atlantic immigrants establish in far western Mediterranean but in recent years, a number of species have been detected expanding east into the central Mediterranean [*Bianchi*, 2007]. The opening of the Suez Canal in 1869 resulted in continuing migrations of tropical species from the Red Sea [*Galil*, 2008]. Until recently, the vast majority of these remained confined to the south-Mediterranean. Recent warming has coincided with the expansion of both native and exotic thermophilic species into the colder reaches of the northern Mediterranean and an increase in invasion rates of both Atlantic and Indian Ocean species [*Lasram and Mouillot*, 2009]. Invasion rates through the Suez Canal have increased by 150% in recent decades [*Raitsos et al.*, 2010]. The vast majority of evidence is supplied from first occurrences of fish species (Figure 30-15c) but evidence is noted across a range of species including mysids (crustaceans), and hydroids [*Chevaldonné and Lejeusne*, 2003; *Puce et al.*, 2009]. The replacement of cold-water species by warm-water species and establishment of exotic species is likely to influence ecosystem functioning with implications for fisheries [*Lasram et al.*, 2010; *Sabates et al.*, 2006; *Tsikliras*, 2008].

One of the key changes that have been occurring in semi-enclosed seas is the steady contraction of the distribution and abundance of habitat forming species such as corals, seagrass, mangroves, salt marsh grasses and oysters [*Hoegh-Guldberg and Bruno*, 2010]. While the causes for these declines are complex, there is a strong climate change and ocean acidification signal. This organisms provide habitat for hundreds of thousands of species, some of which are highly dependent and will disappear along with the particular habitat involved. Elevated sea temperatures and steadily acidifying oceans have disrupted coral reefs over the past three decades, driving increasingly frequent and intense mass coral bleaching events [*Hoegh-Guldberg*, 1999; *Hoegh-Guldberg et al.*, 2007]. In the Gulf of Mexico, a shift in seagrass fish communities to tropical species has also been observed over the past 30 years [*Fodrie et al.*, 2010b].

_____ START BOX 30-2 HERE _____

Box 30-2. Caribbean Sea – Large-Scale Ecosystem Changes

The Caribbean Sea is part of the Western Atlantic Ocean and covers an area of 2.75 million km^2. Bordered by Mexico and 11 Central and South American countries to the south-west and 22 island territories to the north-east, the Caribbean Sea is one of the largest salt water seas in the world.

Natural resources within the Caribbean Sea were abundant prior to contact with Europe in the 15th century. Mangrove, salt marsh, seagrass and coral reef ecosystems provided habitat to a significant proportion of global marine and coastal biodiversity. These natural resources provided abundant food requirements for indigenous inhabitants of the Caribbean, and today continue to be provide food and employment to coastal communities. Ecosystems like coral reefs attract tens of millions of tourists to the region each year, providing import income to communities and governments. Caribbean coastal ecosystems like mangroves and coral reefs provide services such as shoreline protection and fisheries provide locals with significant food and income.

Human populations have increased rapidly over the past century with over 43 million people living within 30 km of Caribbean coastlines today. This has led to increased pressure on marine resources, which have undergone significant decline over the past 50 years. The efflux of nutrients and sediments from disturbed coastline, together with the overexploitation of fisheries, has resulted in the decline of coral populations throughout the Caribbean Sea. These burgeoning coastal populations have led to the decline of ecosystems and fisheries throughout the Caribbean Sea region.

Sea temperatures in the Caribbean Sea have also increased over the past 100 years (Box Figure 1) with the highest temperatures being seen in the last decade. Increasing sea temperatures have triggered mass coral bleaching events, which have increased in frequency and intensity since 1979, when they were first reported. Coinciding with the highest levels of heat stress on record at that time, mass coral bleaching reached record levels in the eastern Caribbean Sea in 2005 (Box Figure 2). Over 40% of reef building corals at many sites in the Caribbean died from exposure to these record conditions. While the impacts have not yet been documented in the field, other factors such as ocean acidification appear poised to increase the erosion and decay of the carbonate reef systems produced by coral reefs.

[INSERT BOX FIGURE 1 HERE
Caption: Long-term temperature records from the Caribbean Sea. Temperature anomalies (2.0° x 2.0° pixels) were computed relative to the mean sea temperature (1901-2000) using the NOAA Reconstructed Sea Surface Temperature data set (ERSST). Used with permission from Eakin et al. 2010.]

[INSERT BOX FIGURE 2 HERE
Caption: A. Accumulated heat stress calculated (0.5° x 0.5° pixels) as Degree Heating Week (DHW, Liu et al. (2006)). Generally, values greater than 4°C- weeks generally results in significant bleaching while 8°C-weeks generally results in widespread bleaching and mortality. B. Jurisdictional means of Coral bleached; marker colour and size indicates severity as measured by either the percent of live coral colonies bleached (circles), or the percent of coral cover bleached (diamonds). Areas in the eastern Caribbean lost as much as 40% of their coral colonies following almost complete 80% of their coral communities bleached. Used with permission from Eakin et al. 2010.]

The combination of local and global factors has had profound effects on benthic communities throughout the Caribbean Sea. Reef-building coral populations that dominated many reef systems prior to 1970 have been replaced by communities of seaweeds and other non-coral organisms. These changes reduce the appeal of coastal environments to industries such as tourism and ability of coastal ecosystems to contribute other services such as shoreline stabilisation and defence, and sand production for beaches. Climate projections suggest that ocean warming and acidification will continue, with even average temperatures passing the known thresholds for thermal stress in the Caribbean Sea when ocean temperatures attain a further 1°C around the middle of this century Simpson et al (2009). Unlike many ecosystems that are threatened by climate change in the future, coral reefs have already experienced major declines due to high temperature impacts such as bleaching and disease. In the three decades since mass coral bleaching was first seen in the Caribbean, there have now been six thermal stress events that have caused significant bleaching and death of corals (Box Figure 3). These changes will continue to reduce the contribution of Caribbean marine ecosystems to the well-being of people throughout the Caribbean Sea.

[INSERT BOX FIGURE 3 HERE
Caption: Average of annual maximum thermal stress (DHW) values at reef bearing pixels in the greater Caribbean Sea region during 1985–2006. See Eakin et al 2010 for description of methods and geographic area. Significant coral bleaching was reported during periods with average thermal stress above 0.5°C-weeks, and was especially widespread in 1995, 1998, 2005, and 2010. Used with permission after Eakin et al. 2010 with addition of data for years 2007-2010.]

_____ END BOX 30-2 HERE _____

Shifts in phenology

Analysis of a 33 yr records of copepod abundance in the Mediterranean exhibit an early shift in the timing of peak a or bundance of greater than 4 weeks although for all cold species, the summer/autumn peak abundance has delayed by 2 months or more [*Conversi et al.*, 2009]. The dinoflagellate Ceratium has shown an advance in the timing of peak species richness [*Tunin-Ley et al.*, 2009]. Advancement in the spawning of the filter feeder polychaetes have also been observed that may be a consequence of warming [*Giangrande et al.*, 2010]

Changes in demography, community structure, and condition

In recent decades, mass mortality events of benthic invertebrates have been linked to elevated sea temperatures during climatic anomalies [*Cebrian et al.*, 2011; *Cerrano et al.*, 2000; *Garrabou et al.*, 2009; *Parravicini et al.*, 2010]. Habitat forming species such as gorgonians and sponges have been impacted by sudden warming to depths of 50m [*Cebrian et al.*, 2011; *Cerrano et al.*, 2000]. In the Mediterranean, the period of stratification during the summer months has lengthened since early 1970s leading to ~40% lengthening of summer conditions when high temperatures and low food availability prevail [*Coma et al.*, 2009]. The frequency of marine mucilage (accumulation of organic matter which hosts pathonogenic microbes) occurence in the Mediterranean over 200 years has increased almost exponentially in recent decades after an absence of 40 years [*Conversi et al.*, 2010; *Danovaro et al.*, 2009]. In 1987/88, there was a switch from red tides to mucilage events, the mechanisms are unknown but may have been driven by the changes in circulation and modification of salinity and nutrient budgets [*Conversi et al.*, 2010]. Mass mortalities associated with thermodepedant pathogens also appear to be increasing in prevailance [*Bally and Garrabou*, 2007; *Cerrano et al.*, 2000; *Vezzulli et al.*, 2010].

Reef building corals have shown dramatic changes over the past few decades in the Caribbean Sea, with major changes in the structure of the subtitle communities, especially with respect to coral reefs [*Eakin et al.*, 2010; *Hughes*, 1994], Box 30-1, WGII CH6). While burgeoning coastal populations, unsustainable coastal practices, and marine resource were undoubtedly major drivers behind these changes, rapid increases in mass coral bleaching have escalated the risk of mass coral bleaching six-fold since 1990 [*Eakin et al.*, 2010]. Conditions in 2005 resulted in the mass mortality of reef building corals across eastern Caribbean Sea. Other regions such as Southeast Asia have experienced similar increases in sea temperature and mass coral bleaching risk, with 2010 seeing very high temperatures and associate of mass coral bleaching across much of Southeast Asia. Rates of warming in Southeast Asia range between 0.1 and 0.4°C per decade, which has pushed corals closer to the temperatures at which they bleach [*Peñaflor et al.*, 2009]. Similar episodes though less is known about them have occurred in the Arabian Gulf and the Red Sea. The increase in the frequency of mass coral bleaching has driven elevated levels of coral disease and mortality. Increase coral disease has been directly linked to thermal stress is [*Haapkylä et al.*, 2010; *Heron et al.*, 2010].

The recent occurrence of rare mass-flowering events in the Mediterranean seagrass, *Posidonia oceanica*, and an increase in shoot mortality appears to be associated with warming temperatures, possibly as the result of thermal stress [*Diaz-Almela et al.*, 2007; *Marba and Duarte*, 2010]. Similar flowering responses associated with thermal stress have been recorded for seagrass species in southern Australian waters.

Alteration of pelagic food-web dynamics in the north-western Mediterranean point to a regime shift in the late 1980s [*Conversi et al.*, 2010; *Molinero et al.*, 2008]. For example, copepod biomass has doubled but with a trend towards smaller species and warmer-water species [*Conversi et al.*, 2009]. The dinoflagellate genus Ceratium has shown a progressive disappearance from surface waters in the north-west Mediterranean as well as a shift to earlier timing of peak species richness [*Tunin-Ley et al.*, 2009].

Biological evidence of a regime shift in the Baltic with a decline in fish recruitment from mid 1980s following a period of increasing recruitment in the 1970s [*Brunel and Boucher*, 2007]. Long term trends suugest a role of climate change interacting with short-term climate signals such as NAO and fishing impacts [*Brunel and Boucher*, 2007]. Phytoplankton communities in the western Baltic and Kattegat show a decline in biomass and change in overall composition since monitoring commenced in 1979 correlated with a reduction in nitrogen loading and warming sea surface temperatures [*Henriksen*, 2009]. During 1987-1989 an usually high dinoflagellate biomass was observed. Several new species of phytoplankton were also recorded that were not present in historical surveys around the beginning of the 20th century [*Henriksen*, 2009]. Add Kraberg et al discussion of regime shift.

Calcification

Evidence is emerging of changing growth rates in corals in the shallow semi-enclosed seas. Responses are highly variable among reefs and species and are likely the consequence of environmental stress such as eutrophication and pollution [*Castillo et al.*, 2011]. However, analysis of cores from colonies of the massive coral *Diploastrea heliopora* in the Red Sea revealed a 30% reduction in skeletal growth rate since 1998, a year of anomalously high temperatures [*Cantin et al.*, 2010]. The corals appeared to have recovered from a previous short-lived warming event in the 1940s within a few years but since 1998 sea surface temperatures have remained relatively elevated comprising the coral recovery. However, analysis of cores from *Porites* and *Cyphastrea* reveal conflicting results with an increase in calcification in the former and no trend in the later [Cantin unpublished, I've emailed Neal to check] Add discussion re species specific responses, potential higher sensitivity of branching corals and loss of structural complexity? Any examples from Caribbean or coral triangle? => dont know - will check.

Comprehensive measurements on long-lived corals growing across the Great Barrier Reef have revealed that rates of coral calcification began decreasing sharply in 1990 [*De'ath et al.*, 2009]. Similar observations have been made for corals growing in Thailand [*Tanzil et al.*, 2009]. These challenges for coral reefs appear to be partially responsible for the loss of significant amounts of coral cover on reefs over the past several decades. Bruno and Selig (2007) documented the large-scale loss of reef building corals from reefs across Southeast Asia and the Western Pacific. Examining measurements of coral cover going back almost 50 years, Brunei and Selig (2007) documented large-scale losses approaching 50% since the early 1980s across the south-east Asian and Western Pacific, including the Great Barrier Reef which is well protected against local stress factors. Similarly, the large-scale loss of reef building corals from the Caribbean Sea (six-fold decreases since 1977, [*Gardner et al.*, 2005]). These broadscale changes close to and far from human settlements have prompted some to speculate that global factors are central to the changes. In this respect, record impact events such as that is occurring in 2005 across the eastern Caribbean [*Eakin* *et al*., 2010] have prompted many to conclude that climate change and ocean acidification are major drivers of change within coral reef ecosystems [*Eakin et al*., 2010; *Hoegh-Guldberg*, 1999; *Rogers*, 2009].

30.4. Projected Integrated Climate Change Impacts (Regional Variation, by Scenario and Time Slice)

The changes in the physical and chemical nature of the ocean that have occurred over the past 50 years have resulted in strong influences on marine organisms, ecosystems and processes. If current trends in the chemical and physical conditions continue, the distribution and abundance of many marine species will be substantially changed along with ecological processes and services that are important for human populations living in the ocean basins and semi-enclosed seas. In the longer term, the nature of these impacts will depend on the extent to which human activities are constrained in terms of their influence on global warming and ocean acidification. In this section, projected climate change impacts on the world's oceans are explored with respect to time slices. Two time slices are explored. The first being near-term changes up to 2050, and the second being long-term changes from 2050 onwards. In both these cases, coverage of the oceans remains at a fairly coarse scale, and consequently detailed discussion of regional variation is somewhat restricted.

30.4.1. Near-Term Changes to Ocean Climate (up to 2050)

30.4.1.1. Physical and Chemical Changes

The way that the future unfolds for the earth and its ocean depends on how natural and anthropogenic forcing evolves over time. Due to inherent uncertainty within the Earth's systems and the global circulation models. For this reason, we use physical and chemical trends from the past 50 years to construct a single scenario for 2050, irrespective of the different climate forcing expected under different socio-economic pathways, which are indistinguishable from the various Representative Concentration Pathways (RCP). We then use our current understanding of how biological systems are responding to these types of changes, and construct an understanding of how climate change and ocean acidification are likely to impact the ocean and its ecosystems. This approach leads to a simplified understanding of the changes that are likely in the future, and the challenges that we will face as a global society as the world's oceans continue to change.

Ocean heat content is currently increasing at the rate of 0.40 x 10^{22} J yr^{-1} (WGI). As a result, sea surface temperature is projected to warm over the next two decades by 0.24°C per decade (WGI Figure 12.38) with the greatest changes occurring at higher latitudes. Extrapolating out to 2050, oceans will be 0.96°C warmer than they are today. Specific rates of warming vary with latitude and geography (Figure 30-16). At the same as sea temperatures are increasing, levels of atmospheric CO_2 are increasing at the rate of over 2 ppm per year [*Hofmann et al*., 2009] and will reach levels of 460-470 ppm by 2050. This will result in a decrease in pH of slightly more than 0.1 pH units (Figure 30-5a,b; 450 ppm), with a further decrease in the hydrogen ion concentration of around 30%. As a result, the carbonate chemistry of the world's oceans will continue to change, with a further decrease in the global Aragonite Saturation State of at least 1.0 (Figure 30-5c, 450 ppm). This will result in the contraction of alkaline waters to increasingly lower latitudes [*Cao*, 2008].

[INSERT FIGURE 30-16 HERE
Figure 30-16: *Placeholder figures for Sea Surface Temperature (SST). A. Average sea surface temperature (2001-2010). B. The rate of change in SST (2001-2010 compared to 1951-1960). C. Sea temperatures in 2050 calculated by adding the change in SST over the past 50 years (2001-2010 versus 1951-1960). These figures will be replaced with appropriate advice from WGI.*]

Increases in ocean heat content will drive thermal expansion of the ocean, which along with increased discharge from terrestrial glaciers will drive accelerating sea level rise. Assuming conservatively that the rates of sea level rise over the next 40 years will be approximately similar to today (3.4 ± 0.4 mm/yr; [*Nerem et al*., 2010]) sea levels will have increased by approximately 13 cm, which when combined with high-intensity storm systems [*Knutson et al*., 2010], will increase inundation of coastal habitats and erosion. While still the subject of considerable debate

[*Emanuel*, 2005 ; *Emanuel et al*., 2008; *Knutson et al*., 2010; *Landsea et al*., 2010; *Landsea et al*., 2006; *Webster et al*., 2005], projections based on theory and high-resolution dynamical modeling consistently indicate that climate change will cause the intensity of tropical cyclones to shift towards stronger storms (2-11% stronger by 2100 although the total number of cyclones is expected to decrease by 6-34% [*Knutson et al*., 2010]. As the hydrological cycle intensifies due to warming, precipitation rates within 100 km of storm centers will increased by 20%. How these parameters for storm frequency and intensity will change depends on the ocean basin involved, as well as showing substantial differences between modeling studies.

30.4.1.2. Biological Changes

The physical and chemical changes that are expected over the next 40 years will significantly change the circumstances under which marine ecosystems exist. Many of the trends reported over the past decade will continue and intensify. Using the average all rate of change in distribution (49.2 ± 5.6 km per decade, Figure 30-9; Poloczanska et al. 2011), is expected that many marine organisms will shift 200 km toward higher latitudes, with the retraction of their ranges at lower latitudes by similar amounts. The ability for range migration, however, does depend on the presence of available habitat. The consistency of these changes with climate change (7 out of 9 taxonomic groups; particularly seabirds and copepods) suggest that future trends will continue in this direction. Similarly, the average change in the phenology of a range of taxa (4.9 ± 0.8 days per decade, Figure 30-9; Poloczanska et al. 2011) suggests that the timing of specific events within the biology of the oceans will on average change by around 20 days. These projections, however, assume linear behavior within the response of marine organisms and ecosystems which may not be appropriate as the extent of change deepens. In this respect, non-linear characteristics are likely to arise such as impacts arising from the mismatch between the presence of larval stages in the water column and suitable prey, or interruption to migratory patterns being brought about by changes to sea temperature [*Hoegh-Guldberg and Bruno*, 2010]. The behavior of many organisms exhibit non-linear physiological properties, which lead to distortions within food webs as temperature increases. With increasing evidence of disruption to ecological relationships and events, changes of this size are expected to present substantial challenges to marine ecosystems and their human dependents [*Duarte*; *Hoegh-Guldberg and Bruno*, 2010; *Moran et al*., 2010; *O'Connor et al*., 2009].

Habitat forming species such as reef-building corals, sea grass, mangroves and salt marsh plants are undergoing a steady contraction [*Hoegh-Guldberg and Bruno*, 2010] and are likely to continue to do so [*Hoegh-Guldberg et al*., 2007]. The reasons for the overall contraction of these important habitat forming species appears to be related to a combination of both local and global stresses. Coral reefs appear to be contracting rapidly (1-2% per annum [*Bruno et al*., 2007; *Hughes et al*., 2011] which will mean (if this trend persists) that 40-80 percent of the coral cover currently covering tropical reef systems will have been lost by 2050. Coral reefs also bleach extensively when they reach 1°C above the current summer maximum temperatures, which is used as a proxy for satellite predictions of where and when coral bleaching is likely to occur [*Strong et al*., 2006; *Strong et al*., 1996]. With sea temperatures currently increasing at the rate of around 0.2°C per decade, sea temperatures will be at this level around the middle of the current century. As with many impacts of climate change, the extremes are extremely important in determining the impacts on natural ecosystems. In this case, the heat stress events experienced by coral reefs around 2050 will exceed by several fold those that are currently causing the mass mortality of corals on tropical reefs worldwide [*Donner et al*., 2005]. Under these circumstances, it is very likely that coral dominated ecosystems will be in rapid decline by 2040-2050. Evolutionary adjustment of thermal thresholds by 1.5°C would postpone this projection by 50-80 years. However, evidence for the rapid evolutionary adaptation of slow-growing, long-lived organisms such as corals is absent and extremely unlikely [*Hoegh-Guldberg*, 1999; *Hoegh-Guldberg et al*., 2007]. Other habitat organisms such as kelp appears to be also contracting as a result of increasing sea temperatures, making vulnerable another large number of resident species and ecosystem processes [*Steneck et al*., 2002]. In this case, interactions between thermocline depth, nutrient supply and temperature appear to have strong influences over the distribution of kelp forests [*Ling et al*., 2009a; *Parnell et al*., 2010]. Similarly, mangroves and salt marsh face challenges from rising sea levels, although the outcomes depend on coastal development and other factors which limit the land would progression of these ecosystems as sea levels rise.

Changes to how marine ecosystems function has significant ramifications for the provision of ecosystem services such as the provision of food, building materials, income, cultural significance and broader scale factors such as coastal protection. In the case of coral reefs, an estimated 100 million people depend directly on the resources and ecosystem services provided. Changes to the quality of these resources has serious ramifications for coastal people and societies. Fish provide 50-90% of the animal protein in the diet of coastal communities in the tropical Pacific for example and hence a critically important for food security within this region [*Bell et al.*, 2009; *Dalzell et al.*, 1996].

30.4.2. Long-Term Changes to Ocean Climate (2050 and Beyond)

This section explores the longer term changes that are likely under scenarios of the futures generated by the Representative Concentration leader Pathway (RCP) methodology used in AR5 to develop credible scenarios of future. The RCP approach used in AR5 include considers "to climate mitigation in addition to the traditional 'no climate policy' scenarios." In this section, the consequences of the different RCP pathways will be considered for each of the ocean basins and the semi-enclosed seas. At the outset, RCP2.6 is distinctly different from the other three scenarios in that atmospheric CO_2 concentrations peak at around 490 ppm well before 2100, leading to the stabilization of radiative forcing and some stability to ocean temperatures and acidities (Ref to WGI). Stabilization of environmental changes is essential if the redistribution of marine ecosystems is to be able to occur, and for the current contraction of many ecosystems to stall and eventually reverse. Conditions within RCP2.6 are also such that temperatures and acidities remain in the range mostly tolerated by marine organisms.

Use model-based projections within chapter 12 - STILL TO COME, Waiting on information from WGI on model projections. Need to have specific information for each ocean basin and, if possible, the semi-enclosed seas. May contract this section if these projections are not possible or lack enough unique detail for each of the ocean basins and semi-enclosed seas.

30.4.2.1. Indian Ocean

[TBD]

30.4.2.2. Pacific Ocean (North, South, South China Sea, Coral Triangle)

[TBD]

30.4.2.3. Atlantic and Caribbean

[TBD]

30.4.2.4. Semi-Enclosed and Closed Seas (Mediterranean, Baltic)

[TBD]

30.5. Key Vulnerabilities and Risks for Major Ocean Systems

The key vulnerabilities and risks for major ocean systems were assessed using the framework outlined by [*Schneider et al.*, 2007] in Ch 19 of WGII of AR4. This approach defines vulnerability to climate change as "the degree to which (these) systems are susceptible to, and unable to cope with, adverse impacts. The concept of risk, which combines the magnitude of the impact with the probability of its occurrence, captures uncertainty in the underlying processes of climate change, exposure, impacts and adaptation." The framework promoted by [*Schneider et al.*, 2007] involves seven criteria which rules are used here to assess key vulnerability and risks for a number of major ocean systems and human activities (Table 30-4).

[INSERT TABLE 30-4 HERE
Table 30-4: Key vulnerabilities and risks for the world's oceans.]

Coastal ecosystems represent a key vulnerability where the magnitude of the impact is high due to the number of people living and depending on coastal resources worldwide. As outlined in this chapter and other assessments (Poloczanska et al. 2011), changes are occurring rapidly within coastal ecosystems such as coral reefs and kelp forests with little potential for these impacts to be reversible in timeframes shorter than that of centuries. These changes are very likely to continue, with the potential for adaptation of ecosystems unlikely within the rapidly changing circumstances affecting coastlines all over the world. Similar assessments can be made for the loss of habitat structuring species, exceedance of temperature tolerances, changes in distribution and abundance of species, shifts in phenology, impacts of temperature on larval development and timing, as well as ramifications of declining oxygen levels in the core of the ocean. Impacts of ocean acidification, changes in demography, community structure and condition, reduced marine calcification, declining ocean productivity, invasive species (e.g., jellyfish), shifts in the distribution and abundance of pelagic fish populations, and changes in ocean current strength and direction are also seen as key vulnerabilities and risks to the ocean services being provided within each of the ocean basins and semi-enclosed seas.

In a similar assessment of the key vulnerabilities and risks to human activities, coastal tourism and fisheries were seen as significantly more vulnerable than activities such as shipping (transport), and oil and gas recovery (Table 30-4).

30.6. Economic, Social, and Environmental Futures under Alternative Development Pathways

The world's oceans provide valuable planetary and ecological services which are critical to the well-being of people everywhere. The rapid changes in physical, chemical and biological systems associated with the world's oceans are very likely to reduce these services, and consequently impact human communities and industries. This disruption to these services will continue as long as the global environment continues to change. RCP 2.6 stands out from the other three RCPs in that it is characterized by a peak in atmospheric carbon dioxide of 490 ppm and then a slow decline beyond 2100. RCP 4.5, 6.0 and 8.5 are characterized by stabilization points beyond 2100 at atmospheric carbon dioxide levels of more than 650 ppm. Stabilization at these concentrations of atmospheric CO_2 are likely to lead to disruptive changes in the physical, chemical and biological state of the ocean which will have major impact for the planetary and ecological services provided by oceans. While there is increasing and serious risk as one approaches 450-500 ppm [*Hoegh-Guldberg et al.*, 2007; *Richardson et al.*, 2011], the risks of unmanageable and catastrophic consequences become unsustainable for most ecosystems, Earth systems, and consequently human dependents [*Smith et al.*, 2009]. For this reason, this discussion centers on describing two broad economic social and economic futures: that of RCP2.6 (490 ppm and under) and those above RCP 4.5, 6.0 and 8.5 (650 ppm and higher).

30.6.1. Global Oceans under RCP 2.6

The next 40 years will see a continual progression towards atmospheric CO_2 levels of 490 ppm and a further increase in average global temperature of around 0.8°C. Ocean temperatures will increase by 0.6°C and will acidify by a further 0.1 pH units. This increase is very likely to continue to put pressure on marine organisms and ecosystems, leading to changes in their distribution, community structure, biological diversity, phenology, structure, and the physiological condition (Table 30-2). The current decline in ecosystems such as coral reefs and mid-ocean gyre systems will continue, with the very likely loss of an additional 40% of coastal ecosystems such as coral reefs. This would result in substantial impacts on ocean ecosystems such as coral reefs, kelp forests and phytoplankton. Assuming the current rate of decline (1-2% per year; [*Bruno et al.*, 2007] in the area occupied by coral dominated reef systems, for example, a further 50% of the world's coral reefs will have been transformed into low coral dominated habitats by the middle of the current century. Along with these changes in coral cover would be a loss of habitat for a large number of other species [*Carpenter et al.*, 2008; *Hoegh-Guldberg et al.*, 2007; *Quero*, 1998]. The changes to marine ecosystems will decrease the provision of services that significantly support human communities, potentially reducing fisheries, income from activities such as tourism, and other indirect contributions such as to human cultures and coastal protection. These changes in global climate will combine with local scale stresses to continue pressuring ocean resources [*Halpern et al.*, 2008]. The overall conclusion in an RCP 2.6 world is that marine resources will continue to undergo rapid change with generally negative consequences for most organisms and ecosystems.

Rapid action to reduce emissions over the century can potentially lead to concentrations of atmospheric CO_2 which peak at approximately 490 ppm by the mid to late part of this century. This would result radiative forcing of approximately 3 W m^2 and a rise in average global temperature of a further 0.5-1.0°C. By the mid to late part of this century, ocean temperatures would be around 2°C warmer than they are today. The important characteristic of RCP2.6 is that conditions will begin to stabilize by the mid to late part of this century. Stability will allow many biological systems to essentially 'catch up' . The redistribution of organisms and ecosystems will occur, and under these new stabilize conditions, ecosystems such as coral reefs, kelp forests and pelagic systems might expand again as organisms were able to migrate and begin to expand into areas of the world which matched their preindustrial climate. These changes will take time but will eventually lead to stabilise ecosystems by the early part of next century, with the potential for ecological goods and services to slowly increase back to levels prior to the mid 1950s.

The changes in the goods and services provided by oceans to human communities would impact societies throughout the world. Communities that are dependent on food and income from fisheries will experience changing catch composition and volume. Changes in primary production may have major impacts on food chains leading to fish. Global fisheries caches since 1950 have been increasingly constrained by the amount of primary production [*Chassot et al.*, 2010]. If there is a reduction in primary production, it could have global negative impacts on fisheries catch and exacerbate current trends of overfishing. This may not only lead to food security issues but also affect the human well-being and economies of many fishery-dependent countries [*Chassot et al.*, 2010].

While most impacts are likely to be negative, there may be social and economic benefits associated with new opportunities as the relative geographic location of fisheries stock changes. For example, tuna populations that are migrating as a result of increasing ocean temperatures may lead to new opportunities for some Pacific nations while others may suffer the consequence of stock which travels well outside their national waters. Artisanal fisheries which support hundreds of millions of people throughout the world they also show new opportunities as alien species begin to penetrate new habitats at high latitudes. For many human communities, however, the decline in coastal ecosystem quality such as that seen throughout tropical areas of the world is likely to lead to lower amounts of protein coming from these sources. This will lead to increasing pressure on other resources as these people seek to find daily food and protein to replace that lost from marine ecosystems and fisheries.

In addition to the chemical and physical changes that are occurring within the world's oceans, changes to sea level will place millions of people and their coastal infrastructure under pressure [*Dasgupta et al.*, 2009]. Under RCP 2.6, sea level rise would continue well into the next century but will slow soon afterwards. These changes will place coastal communities and infrastructure under increasing pressure from inundation, damage from storm surge, and inundation of coastal aquifers and water sources. These challenges and scenarios are dealt with in the accompanying chapter on coastal and low-lying areas (WGII, Ch5).

The majority of impacts up to the middle and late part of the current century will have negative consequences for human communities and will require significant adaptation responses in order to minimize the costs for human well-being. Many industries will be under pressure as elements of the biosphere respond to the changes in the chemistry and physical nature of the ocean. As atmospheric carbon dioxide levels reach 490 ppm and begin to stabilize, biological systems will redistribute themselves across the planet to those areas where they find environments and habitats similar to those that they had evolved to use. This redistribution will take time and is likely to continue into the early part of next century. As a result of these changes, human communities and industries will need to be flexible, and will require support in order to adapt to the new distribution of biological elements.

30.6.2. Global Oceans under RCP 4.5 and Beyond

As discussed before, changes over the next 40 years will be very similar under the four RCP scenarios central to AR5. Increasing amounts of damage and change will occur to natural ecosystems, which will have consequences for the health, well-being and resources available to human communities from wide number of locations. As discussed with respect to RCP 2.6 many of these changes will have consequences for human communities and will require significant adaptation responses in order for human well-being to be preserved. Around the middle of the current century, RCP2.6 begins to differ significantly from the other three RCP scenarios. While the atmospheric carbon dioxide content and radiating forcing associated with RCP 2.6 reaches a maximum (490 ppm, 3 Wm^{-2}) and begins to decline as the century closes and begins to decline, 4.5, 6.0 and 8.5 rise to much higher atmospheric carbon dioxide concentrations (650 ppm and higher) and radiative forcing (4.5 Wm^{-2} and higher).

These changes to the global climate will almost certainly drive some of the most significant changes seen in the ocean over the past 40 million years. Temperatures are likely to rise well above 3°C which would have a dramatic impact on ecosystems such as coral reefs and other benthic systems. Exposure of corals living on coral reefs today to temperatures just 1°C higher than the summer maxima results in mass coral bleaching [*Strong et al.*, 2006], and temperatures rising to 3°C above the summer maxima for a region for even short periods of time (<6 weeks) will result in mass mortality events [*Hoegh-Guldberg*, 1999; *Hoegh-Guldberg et al.*, 2007]. Increases in sea temperature of this magnitude are very likely to remove functional coral dominated reef ecosystems. Similar sensitivities are being found in a range of other benthic ecosystems and suggest that similar outcomes face a broad range of benthic and pelagic ecosystems [*Hoegh-Guldberg and Bruno*, 2010].

Other parts of the ocean face significant changes in these upper scenarios, including the possibility of widespread deep ocean anoxia which is likely to have a fundamental impact on the oceans. How these changes are likely to impact planetary services associated such as the regulation of atmospheric gas concentration is still a matter of discussion although the paleontological evidence of ocean warming, the collapse of circulation and resulting ocean anoxia [*Zachos et al.*, 2008] driving major changes to the biosphere such as seen during the mass extinction event which occurred during the Paleocene-EoceneThermal Maximum (PETM; when CO_2 was also very high) represents a distinct possibility if atmospheric carbon dioxide levels are pushed beyond 490 ppm [*McInerney and Wing*, 2011]. Understanding the combined impacts associated with these scenarios is extremely difficult given the large range of changes interactions that are likely between chemical, physical and biological elements. Needless to say, entering such a scenario would be catastrophic human beings and would result in changes that would defy any attempt at adaptation.

30.7. Sectoral Impacts (in Light of Interacting Stressors and Uncertainty)

The ocean supports a wide array of sectors, especially if coastal regions are included. Given that the IPCC AR5 chapter on coasts and low-lying areas, discussion here will be restricted to those sectors that have a major association with the ocean as opposed to coastal societies. It is expected that coastal activities that are impacted by changing ocean conditions will be dealt with by this previous chapter.

30.7.1. Fishing

Fishing pressure and pressure from the ocean climate are together the two most important factors impacting recruitment and growth in fish stocks. A sustainable fishery implies that the fishing pressure has to be balanced against the basic productivity of the ecosystem and how the biomass is transformed to harvestable resources. The physical forcing and the development of the ocean climate are key elements for the productivity, but there is no uniform response to climate change across the world's marine ecosystems. It impacts productivity of in a diversity of ways depending on the critical processes for productivity in each ecosystem. A synthesis of four global models on phytoplankton production indicates an average decline in the world's phytoplankton production of 6 % through the 21st century [*Steinacher et al.*, 2010]. The reduction is most apparent in the large ocean gyres, while at high latitudes the production increased (Figure 30-17). Similarly to Steinacher et al. (2010), [*Ellingsen et al.*, 2008] found the phytoplankton production to increase at high latitudes. For the Barents Sea they modeled an increase by 8 % for period onto 2070. Also [*Mueter et al.*, 2009] found that primary production in high-latitude marine ecosystems in the North Atlantic and North Pacific increased with increasing temperature. In the world's five large upwelling ecosystems the changes are adverse [*Barange and Perry*, 2009], apparently an increase in the Canary Current and the California Current and a substantial decrease in the Benguela Current and Somali Current. In the Chile-Peru upwelling system the productivity increases in south and decreases towards equator [*Steinacher et al.*, 2010]. In other coastal areas the changes are as well adverse.

[INSERT FIGURE 30-17 HERE
Figure 30-17: Left panel: Modeled mean primary production of four global models under preindustrial conditions (1860-1869). Right panel: Rate of change from preindustrial time to the end of 21st century (2090-2099). Source: Steinacher et al. (2010).]

The major regions for fish production are confined to three types of ecosystems mentioned above, i.e.: 1) high-latitude ecosystems, 2) The large upwelling ecosystems and 3) in coastal regions. For high-latitude ecosystems both predicted changes in the primary production [*Steinacher et al.*, 2010] and past observed changes in the abundance of boreal fish stock [*Drinkwater*, 2006; *Toresen and Østvedt*, 2000] indicate an increase in the potential for fish production under climate change. For the five large upwelling ecosystems the results on primary production are adverse and so it is for other coastal regions. There are, however, uncertainties linked to the productivity of the upwelling and coastal regions that might alter the conclusions on fisheries. Firstly, more frequent events on low-oxygen or anoxic situations (Hofmann et al. 2011 in press) might result in lower productivity or more frequent events on mass mortality of fish species. Adverse effects of lower oxygen will be greater for demersal fishes than pelagic fishes (e.g. Heath et al 2005). Secondly, correct modeling of coastal upwelling and primary production rely on high-resolution wind forcing that is not necessarily sufficiently represented in global models.

In addition to the changes in productivity as a result of climate change, there will also be a change in distribution of natural habitats for species. Except for marine mammals most marine species, vertebrates as well as invertebrates, are poikilotherms with their specific range of ambient temperatures. In addition, most marine organisms also have their specific adaptation to salinity, particularly invertebrates that are heterohaline organisms without osmoregulation. Hence, both change in temperature and salinity will change the natural habitat extents of marine species. Particularly, changes in temperature have been documented to impact distribution of species from plankton to fish [*Beaugrand et al.*, 2002; *Drinkwater*, 2006; *Fodrie et al.*, 2010a]. [*Cheung et al.*, 2009] applied a so-called dynamic bioclimate envelope model together with a global climate model to predict changes in fish species distributions with climate change. The results are largely corresponding with past observations. It implies that species are displaced polewards from the equator, and that species invasions are dominating at high latitudes. Species extinctions are occurring at the extreme ranges, i.e. in the equatorial region of upper extreme temperatures and in the high Arctic and the Antarctic of lower extreme temperatures.

[INSERT FIGURE 30-18 HERE
Figure 30-18: Projected distributional changes in fish species in 2050 relative to 2001-2005 (after Chung et al., 2009).]

In conclusion, high-latitude ecosystems seem to have the potential for increase in fishes, both in number of species and in biomass. In the Arctic there is a potential for increase in biomass, increase in number of boreal species boreal but decrease or collapse of arctic species. Equatorial regions have the potential for decrease in biomass and decrease in number of species and species extinctions. In the large ocean gyres there is a potential for decrease in biomass of fish species. For the large upwelling regions the development in fish abundance and species diversity is more unclear because of the possibility of more frequent development of anoxic conditions, and because of uncertainties concerning the upwelling dynamics.

30.7.2. Transport (Shipping)

Sea transport has been the largest carrier of freight throughout history. Due to economic growth and globalization, world trade since the 1950s has more than trebled [*Gelpke and Visbeck*, 2010], boosting international shipping. While it accounts for > 80% of the volume of world trade (UNCTAD, 2009b), international shipping is a small contributor to the total volume of GHG, accounting for ca. 3% of global CO2 emissions from fuel combustion (IMO, 2009). The international Maritime Organization (IMO) expects emissions from international shipping will increase by a factor of 2.2 to 3.1 between 2007 and 2050 (UNCTAD, 2009a). GHG emissions from international shipping are currently not regulated, but the IMO and UNFCCC have recently intensified and expedited its work in this field. However, in terms of fuel efficiency, maritime transport surpasses other modes such as heavy truck, rail and freight airplane (UNCTAD, 2009a).

Higher temperatures and extreme weather events, intensified by climate change, may more frequently interrupt ports and transport routes and damage infrastructure (UNCTAD, 2009a). Increased frequency and magnitude of severe storms in the ocean can aggravate sailing conditions and potentially pose dangers to ship, crew and the environment (UNCTAD, 2009a), which can lead to a shift to other transport modes that are less vulnerable to weather, but with lower fuel efficiency.

A potentially positive impact of climate change on maritime transport is warming and meltdown of the Arctic. The ice-free season of the Northern Sea Route (NSR) could increase by up to 80 days per year in 2080 [*Rijnsdorp et al.*, 2009]. A fully operating NSR is expected to reduce the sailing distance, for example, between ports in the Europe (e.g., Rotterdam) and the Northeast Asia (e.g., Yokohama) by >40% [*Borgerson*, 2008], decreasing the overall volume of GHG from ships.

30.7.3. Oil and Gas

The impacts associated in energy and climate scenarios with the marine oil and gas industry relate both to the assumed role of the industry in supplying the liquid fossil fuels essential for the transportation sector of the economy, and to the impact of climate change on the industry itself. Historically the development of automobile and aircraft transportation has been near 100% dependent on liquid fuels and this dominance is projected to continue. Continued depletion of oil and gas reserves in shallow water has resulted in a progressive movement to waters 2,000m deep or more, far beyond continental shelves. This brings considerable challenges.

The movement to deeper waters potentially exposes very large scale moored developments to greater storm hazards and higher risk that is not well constrained by the climate/weather projections of today. Offsetting this is the strong trend towards sea floor 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 relating to the effects of methane and methane hydrates (NRC, 2010). Knowledge of the causes and frequency of sub-sea slide events is far less advanced than knowledge and prediction of weather events.

When failures of deep-sea structures, whether surface or deep, do occur they are difficult to control and can bring about severe environmental impacts (US National Commission, 2011) that will add to stressors on marine life both from direct oil impacts and as increased hypoxia [*Kessler et al.*, 2011] that is already associated with ocean ventilation changes and warming. Nonetheless progressively deeper water oil and gas developments are embedded in almost all energy scenarios.

30.7.4. Tourism

Tourism is the world's largest industry. AThe world's oceans and coasts are highly valued by the tourist industry, for a relaxing climates as well as often exquisite marine ecosystems. As a result, climate variability can play a strong influence on both the tourist potential of a location, as well is the day-to-day decision associated with risk of extreme events. The deterioration of coastal resources such as coral reefs can play an important role in deciding whether or not tourists will travel the often long distances to visit these resources. Given that many countries depend on tourism for a major part of their international earnings, the impact of climate change on the quality of tourist resources can have a severe impact on national accounts.

Equally, under mild climate change scenarios, changes in regional climate may have a positive effect on maritime tourism, with a potential shift of tourism towards higher latitudes and colder countries as they warm. Dutch tourists, for example, have an average preferred temperature for tourist destinations of 21°C, with the implication that they will shift their destinations as the climate warms [*Lise and Tol*, 2002]. According to modeling studies such as the Hamburg Tourism Model, this could potentially double tourist income in colder countries and reduce income in warmer countries by as much as 20% [*Bigano et al.*, 2005]. Under higher scenarios, this shift may intensify although changes in the intensity of extreme events such as storms, floods and droughts may begin to affect the shift in tourism towards higher latitudes.

30.8. Adaptation and Managing Risks

Societies can respond to climate change by adapting to its impacts and by reducing GHG emissions (mitigation), thereby reducing the rate and magnitude of change. The Adaptation and mitigation options can be implemented over the next two to three decades, and their inter-relationship with sustainable development. These responses can be complementary (IPCC, 2007, SYR).

Climate change will inevitably lead to more or less simultaneous changes in numerous environmental variables during the coming decades and centuries. Very little is actually known about how the open ocean will affect marine biological communities, especially, when its impact combines the other environmental factors. For instance, marine ecosystem suffers many stressors such as ocean warming, acidification, overfishing, exotic species, pollution that are now playing an important role on marine life. Multiple stresses cause marine ecosystem facing much more vulnerability both in the short and the long term.

However, adaptation can reduce vulnerability to climate change, which can be exacerbated by the other stresses. Societies across the world have a long record of adapting and reducing their vulnerability to the impacts of weather- and climate related events such as floods, droughts and storms (IPCC, 2007, SYR). The related adaptation measures for the marine ecosystem and socio-economic related sustainable development could be chosen in the open ocean according to the impacts of climate change with the other environmental stressors.

A variety of adaptation measures in coastal water could be considered such as walls and storm surge barriers, creation of marshlands/wetlands as buffer against sea level rise and flooding, protection of existing natural barriers [*IPCC*, 2007c]. Intervention strategies to mitigate the impacts of bleaching on reefs such as reef shading, polyp feeding, electrochemical stimulation, symbiont inoculation and wave-powered artificial upwelling may be of future conservation interest [*Baker*, 2008]. Furthermore, reducing catches, restricting fishing and construction of artificial reefs (Islam, G.M., et al., 2011) , allocating fishing rights, fish farming (Nguyen, V.H.,2010), marine protected areas (Game, E.T., et al., 2009; Harmelin-Vivien, M., et al.,2009) – havens for endangered species may be some useful measures to control human overfishing, protect marine biology diversity, raising the productivities and improve resilience of ecosystems. In addition, iron fertilization in the open ocean might be a way to adaptation and mitigation to anthropogenic climate change. And it is also necessary to combat the exotic species for protect the local native marine biological diversity.

Finally, some inter-national strategies including conventions, cooperation and environmental management have to be taken to adapt the combined impacts of climate change and the threat from exotic species and so on would be much more effective, e.g., ex-ante measures, ex-post management and regional cooperation etc. (R. Quentin Grafton, 2010; Nicholas Bax et al., 2003).

30.9. Mitigation Options

As for anthropogenic climate change, mitigation means implementing policies to reduce greenhouse gas (e.g., CO2) emissions and enhance sinks. Many impacts of climate change can be avoided, reduced or delayed by mitigation. One very promising approach to reducing CO2 emissions is CO2 capture at a power plant, transport to an injection site, and sequestration for long-term storage in any of a variety of suitable geologic formations (José D. Figueroa, 2008). Therefore, it may be one of useful mitigation to select suitable sea bed in open oceans to be a CO2 storage location, e.g., exploited oil and gas field under sea, and long-term isolation from the atmosphere.

30.9.1. Fishing

During the second half of the 20th century the world capture fisheries increased nearly 5 times from 20 million tons in 1950 to a peaking value of more than 90 million tons around the turn of the century. The total catches have decreased thereafter. Many fish stocks are today fully exploited or overexploited. Illegal, unreported and unregulated (IUU) fishing, effective implementation of monitoring, control and surveillance (MCS) and overcapacity in fishing fleets are the three main impediments towards sustainable development in the world fisheries (FAO 2010). IUU fishing is particularly impacting top-predator fishes of high value, like tunas. Climate change may amplify the impacts of unsustainable fishery and, hence, accelerate the need to cope with these problems. It is important to develop the implementation of ecosystem-based management rules for the fisheries. This implies that the fishing pressure is balanced against basic productivity in the form of primary and secondary production and of multi-species fish interactions. However, it is important to realize that the capacity for developing such advanced methods is not equal across nations and world oceans.

Benthic biota in shelf regions is particularly impacted by high activity of industrial fishing in the form of bottom trawling. Additionally, trawl fishing has the gear type with the highest fuel consumption. For example, a trawler in Norwegian waters consumes 3.5 times more fuel per kilo fish caught than a fishing vessel using nets or lines and 7 times more than a purse seiner (NOU 2006). Development of new gear types and vessels that reduces fuel consumption and habitat destruction is a strategy for adaptation and mitigation for climate change.

The general impact on fish stocks from climate change is a displacement of fish species towards higher latitudes, and lower abundance and number of species at low latitudes. This implies that catch quotas here must be reduced as biomass decreases. Aquaculture is a rapidly increasing industry and is presently the fastest growing animal-food producing sector (FAO 2010). Aquaculture production has already passed 50 million tons and the expected potential for further increase is large. The increase is particularly occurring in tropical and subtropical regions. Hence, aquaculture could become an important sector to compensate for the loss in wild-fish catches. However, it is important that the farmed species are utilizing lower-trophic level feed to avoid further increased pressure on fish species at higher trophic level and fish that could go directly for human consumption. Development of aquaculture in multiculture where shellfish at the lower end could utilize the nutrient production and eutrophication would be a sound adaptation strategy to sustainable food production.

Fishing is an activity at high risk both in artisan and industrial fisheries. To cope with rough weather conditions or extreme events is always a challenge. Extreme weather conditions might become more frequent under climate change, particularly in tropical and subtropical regions. Modifications in constructions of vessels, harbours, and coastal fishing communities might be needed to meet the challenges from climate change.

30.9.2. Transport

Climate change presents dual challenges for international maritime transport. While reducing its contribution to global warming, it needs to adapt to the impacts of climate change.

Basically, there are three approaches to reduce GHG from maritime transport (Table 30-1). First, advances in technology and energy use can contribute to reducing emissions by replacing older, less energy-efficient or higherpolluting equipment and engines (IMO, 2000). Because most promising alternative techniques do not yet fully compete with diesel engines, shifts to alternative fuels and energy sources would be practically difficult in the short term. However, it was suggested that a switch from diesel to natural gas is possible in some cases (InterAcademy Council, 2008). Regarding biofuels, concerns over their production processes and related implications for food security, climate change and sustainability make their future uncertain. Solar panels and sails – as well as hydrogen-propelled ships and fuel cell power for auxiliary engines – constitute long-term options. Carbon capture and storage technology could also be further developed and applied to the transport sector. Along the supply chain, optimizing vehicle utilization could help mitigate emissions through (a) telematics; (b) intelligent transport; (c) new vehicle and engine design; and (d) information and communications technology-enabled scheduling, planning and routing. Equally, trade facilitation solutions, such as computerized customs data (e.g. Automated System for Customs Data (ASYCUDA)) could have a role to play.

Second, improvements in operational measures can decrease GHG emissions from ships. For example, through rerouting and speed reduction, it was estimated that a short-term CO2 reduction potential of up to 40% is possible (IMO, 2000). Vessel speed reduction is a key strategy to reduce fuel consumption and GHG emissions. Slowing down by 10% can lead to a 25% reduction in fuel consumption (UNCTAD, 2009).

Third, market-based programs may include measures such as taxation, differentiated port fees, shipbuilding subsidies and emissions trading via a cap and trade system. For example, it was estimated that a creative market-based instrument covering all ships can deliver significant and differentiated benefits and could raise 10-45 billion US dollars annually (IMO, 2009). Industry-led voluntary initiatives include, for example, committing to an average emissions rate, known as the benchmark, and promoting specific emission control technologies and preferential contracting of cleanest carriers whereby shippers require shipowners and ports to compete in terms of environmental performance and costs (UNCTAD, 2009).

Adaptation to climate change in maritime transport sector may be achieved through investment and planning decisions, broader transport design, and development plans (UNCTAD, 2009).

To cope with extreme weather events, which can be amplified by rising sea levels, emergency evacuation procedures may be integrated into operations. Smart technologies could be used to detect abnormal events, and infrastructure and equipment resistant to extreme weather events can be developed. Managing these events may involve continuous inspection, better monitoring of infrastructure temperatures, increased maintenance, reduced cargo loads, reduced speed and frequency of service, and changes to ship design. Ships, ports, terminals, warehouses and storage areas may require increased refrigeration, cooling systems and ventilation, resulting in higher energy consumption and CO2 emissions. Finally, stronger ships able to better withstand extreme weather events will probably be required.

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 a direct interest in the Arctic. Goals and decisions of UNFCCC for reducing GHG are principally based on geographical boundaries, but CO2 emissions from maritime transport are largely generated outside national boundaries and ships may be linked to different nations through registration, beneficial ownership and operation (UNCTAD, 2009). Potential mitigation measures and adaptation requirements in maritime transport sector can pose particular challenges for LLDCs, LDCs and SIDs, especially for their already-volatile trade and development prospects.

Increases in the frequency or magnitude of extreme weather events could amplify the costs to maritime transport. Possible linkages between climate-change scenarios and international trade scenarios, such as a number of regional and sub-regional free trade agreement were postulated (UNCTAD, 2009). Climate-change policies could raise industrial and transportation costs, and necessitate changes in infrastructure and design technology.
These potential shortcuts by Northern Sea Route (NSR) could drive competition with existing routes. Ports and terminals in the Arctic need to be able to accommodate ships with an ice class. NSR may promote resource exploration activities in the region.

[INSERT TABLE 30-5 HERE
Table 30-5: Potential mitigation options for international shipping, and potential implications of adaptation in maritime transport (UNCTAD, 2009).]

30.9.3. Oil and Gas

The principle threat to oil and gas extraction in maritime settings is the impact of extreme weather on oil and gas extracting infrastructure. The Atlantic storm season in 2005 was the most active in recorded history causing an unprecedented level of damage [*Trenberth and Shea*, 2006], killing over 3000 people, and making over 1 million people homeless throughout the Caribbean region. The impact on the American petroleum industry was severe. Hurricanes Rita and Katrina hit the American petroleum industry hard, shutting down eight refineries as well as hundreds of oil drilling and petroleum production platforms. This led to a number of unintended consequences, including the release of hazardous materials from industrial facilities and disabled production facilities and platforms. The two hurricanes caused the greatest damage to mobile offshore drilling units in the history of Gulf of Mexico operations [*Cruz and Krausmann*, 2008]. Clearly these operations require reconsideration of one of the consequences of global warming, and this is the likelihood that storm systems will have greater energy [*Emanuel*, 2005 ; *Knutson et al.*, 1998 ; *Knutson et al.*, 2010; *Trenberth and Shea*, 2006]. [Of course, the irony of this situation is hard to escape!].

30.9.4. Tourism

Tourism faces a number of challenges and opportunities within a warming ocean. In the case of the negative consequences of climate change, particularly at lower latitudes, tourism as an industry needs to adapt and manage risks of issues such as reduced ecosystem health, increased risk of extreme events, reduced economic strength of countries in which tourism might be based, and growing poverty as environmental conditions deteriorate. Reduction in ecosystem health can translate as a reduced competitive advantage of one destination over another. The Great Barrier Reef, for example, competitively draws over $6 billion in revenue each year to the Australian economy based on its relative pristine condition when compared to other coral reefs around the world. Repeated impacts of thermal stress and other climate related factors has the potential to reduce this advantage, and lead to substantial losses to the tourist economy. Strategies to reduce non-climate related stresses such as controlling overexploitation of fishery stocks [*Hughes et al.*, 2007] or improving water quality [*Hoegh-Guldberg et al.*, 2007] has the potential to prolong this particular competitive advantage. Risks of extreme events will require greater awareness of reporting systems and potential adaptation of tourist infrastructure to ensure that tourists feel and report that they feel safe at the particular locations. Though unrelated to climate change, the Boxing Day tsunami in 2004 that impacted Thailand and many other Indian Ocean countries highlighted the consequences of the increasing risk of extreme climate events associated with many tourist destinations [*Rigg et al.*, 2005]. Reviewing and building to higher construction standards, as well as having well-developed disaster preparation plans, are essential to any industry that plans to adapt to the consequences of climate change. Other issues such as the steady increase in poverty in many countries as environmental circumstances change will represent increasing challenges for industries planning to maintain quality tourist operations in desired maritime and coastal destinations.

30.10. Adaptation and Mitigation Interactions

There is high confidence that neither adaptation nor mitigation alone can avoid all climate change impacts. Adaptation is necessary both in the short term and longer term to address impacts resulting from the warming that would occur even for the lowest stabilization scenarios assessed. There are barriers, limits and costs that are not fully understood. Adaptation and mitigation can complement each other and together can significantly reduce the risks of climate change (IPCC, 2007, SYR).

[INSERT TABLE 30-6 HERE
Table 30-6: Title?]

30.11. Inter- and Intra-Regional Impacts and Multi-Sector Synthesis

Despite the fact that oceans can be separated into four categories outlined in this chapter, the influence of climate change is operating across the global ocean which is highly connected through currents, physiochemical interactions, weather patterns and species distribution. For example, many species that are found in East Africa are also found throughout the Pacific, some all the way to the Americas. This connectivity also means that impacts from climate change are not restricted to one ocean basin or another. This characteristic becomes clear from Table 30-5 when most ocean basins have very similar patterns of risk and vulnerability. The semi-enclosed oceans have slightly different risks and vulnerability, largely on the part of their disconnected must from the global ocean.

The majority of sectors that use the ocean do so with a fairly low degree of interactivity. For example, although shipping and fishing activities in the open ocean use the same resource, they rarely interact directly. However, these particular sectors are linked through issues such as the price of energy in order to fuel boats and ships to carry out their activities. Equally, many parts of the oceans see potential conflict between tourist values, shipping, fishing, and oil and gas extraction. These interactions can lead to conflict which has been minimised in the case of well-planned coastal and ocean resources. Collaboration among the international community such as that seen with the Coral Triangle Initiative (see Box 30-3) can also play a very important role in maximising the synergies between countries approaching similar problems. These types of international initiatives also highlight the important property of marine systems, and that is they are high degree of flow and connectivity across borders.

_____ START BOX 30-3 HERE _____

Box 30-3. Coral Triangle Initiative – Regional Multi-Lateral Cooperation to Solve Local and Global Stresses

The Coral Triangle stretches across six countries in Southeast Asia and Melanesia and occupies around 6.8 million km^2 (just over 1% of the Earth's surface) including 132,000 km of coastline. Marine and terrestrial biodiversity within this region is unrivalled with the epicentre of the diversity for corals, mangroves, seagrass, fish and many other organisms being found here. In addition to its biological importance, the region also supports 150 million people who rely heavily on coastal resources for well-being. Benefits include food and income from artisanal and commercial fisheries, medicines, building materials, firewood, and income from associate activities such as tourism. Coral reefs and mangroves also provide coastal barriers and stabilise coastal sediments which ultimately protect infrastructure and communities from wave action.

Coastal ecosystems within the Coral Triangle are under a high level of threat from local factors such as coastal deforestation, expanding coastal populations, reduced water quality, pollution, destructive fishing and the overexploitation of many species. Coastal ecosystems within the Coral Triangle are degrading rapidly with the loss of approximately 40% mangrove forests and coral reefs over the past 40 years. Sea temperatures in large parts of the Coral Triangle are increasing at the rate of 0.2-0.4°C per decade (Box Figures 4 and 5), which will soon exceed the known tolerance of organisms such as reef building corals (1-2°C above today's summer maxima) with potentially serious consequences for ecosystems such as coral reefs. Sea levels are also rising rapidly, putting at risk coastal ecosystems such as mangroves and salt marshes as well as human communities and infrastructure, many of which are impoverished and have few options for responding or adapting. Economically important species such as tuna are showing changes in their distribution, which has implications for the ownership and exploitation of these important pelagic fish stocks.

[INSERT BOX FIGURE 4 HERE
Caption: The Coral Triangle includes 6.8 km^2 of ocean territory and 132,000 km of coastline. The boundaries to the Coral Triangle are based on high levels of marine biodiversity.]

[INSERT BOX FIGURE 5 HERE
Caption: Trends in sea temperature (0.5° x 0.5° pixels) for the period 1985 to 2006 as calculator from biweekly satellite data collected by the National Oceanic and Atmospheric Administration (NOAA) In Washington DC.]

Building the ecological resilience of coastal and oceanic ecosystems, while reducing unsustainable exploitation, has the potential to reduce the impact of climate change and ocean acidification. Improving coastal water quality and protecting key ecological functional groups such as herbivorous fish increases the ability of ecosystems such as coral reefs to bounce back from disturbances such as mass coral bleaching. Expanding the protection of key habitats such as mangroves and seagrass meadows that act as nurseries for pelagic fish stocks can deliver significant benefits in maintaining important fisheries, many of which are fished in open ocean waters. In this respect, reducing coastal deforestation and maintaining the integrity of coastal catchments can have significant benefits to natural ecosystems and their human dependents.

The complex political geography of the Coral Triangle can frustrate actions to build the resilience of the region's natural ecosystems and take the necessary measures to reduce the impact of current and future impacts from climate change. Regional cooperation between Coral Triangle countries may provide a solution. Multilateral cooperation was stimulated by President Susilo Bambang Yudhoyono of Indonesia in August 2007 which led to the Coral Triangle Initiative on Coral Reefs, Fisheries, and Food Security (CTI) which involves region-wide 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. The six CT governments launched a regional plan of action at the World Ocean Conference in May 2009, Manado, Indonesia. The Coral Triangle Initiative has begun to focus and coordinate the efforts of six governments, and has led to region-wide cooperation over the management of pelagic fisheries, as well as the management of coastal ecosystems. This multilateral regional cooperation has the potential to serve as a model for other regions where challenges associated with fisheries, natural resource management, food security, and human well-being are inextricably connected across national borders.

_____ END BOX 30-2 HERE _____

30.12. Concluding Remarks

30.12.1. Major Conclusions

There are a number of major conclusions that can be drawn as regards the impact of climate change and acidification on the world's oceans.

Our understanding of the ocean is beginning to accelerate from a fairly low base relative to our understanding of the terrestrial components and ecosystems. Smaller amount of information on the oceans relative to terrestrial systems has arisen primarily as a function of the difficulty of accessing marine environments and ecosystems.

Interpreting the changes that are occurring within the world's oceans is complicated by patterns of variability such as the Pacific Decadal Oscillation, El Niño Southern Oscillation (ENSO), Benguela Niños, and the North Atlantic Oscillation (NAO).

The Earth's ocean represent represents a major component of the climate system within which the biosphere and humanity operates. It absorbs over 90% of the extra heat generated by the enhanced greenhouse effect, is a major sink for atmospheric carbon dioxide, and is responsible for 50% of the global primary productivity.

Previous assessments have noted that the ocean is warming rapidly to deaths of at least 3000 m and that the ocean is steadily acidifying under the increasing partial pressure of carbon dioxide in the atmosphere. Biological systems such as coral reefs and open water pelagic communities were noted as being impacted as a result of these rapid environmental changes.

Since the last assessment, the pace of this change has either stay the same or increased, with changes being reported in a much wider array of physical, chemical and biological systems. These impacts are affecting all ocean basins

(Pacific, Atlantic, Indian) and associated semi-enclosed seas. Impacts vary in terms of intensity from these different sub-regions.

The warming of the upper layers of the ocean is leading to reduced mixing of nutrients into the photic zone, which appears to be reducing the productivity of some areas of the ocean. Nutrient poor areas of the Pacific and Atlantic Oceans increased by 6.6 million km^2, or 15% over the period 1998 to 2006. A longer-term study of the world's oligotrophic gyres has revealed similar changes in the Pacific and Indian Ocean but not for the Atlantic Ocean.

Recent responses by other biological systems are highly consistent with the direction of change expected under rapid climate change. Over 74% of 2,006 observations showed responses that were consistent with the patterns of warming within the ocean. Although many of the observations were clustered in the north Atlantic, most regions showed similar consistent trends.

There is abundant evidence that a wide range of taxonomic groups are shifting their distributions to higher latitudes at the average rate of 49.2 ± 5.6 km per decade. At the same time, the timing of behavioral events (e.g. spawning, migration) have shifted at the rate of 4.9 ± 0.8 days per decade. These changes are occurring in all oceans and will have major implications for the composition of natural ecosystems, especially when it comes to novel ecological assemblages and the spread of alien species and pests.

The Atlantic Ocean in North Sea have been warming and acidifying steadily. These changes are associated with major changes in biological systems which are consistent with the direction and speed of climate change (overall 77.5% of 844 published observations). Changes are being seen in the distribution and abundance, phenology, demography, committee structure, physiological condition and calcification of Atlantic species.

A similar changes are occurring in the Pacific Ocean, albeit at a slightly slower rates of change. A large proportion of Pacific studies have shown changes in organisms and ecosystem processes that are consistent with the expected direction of climate change (70.2% of 533 total observations). As with the Atlantic Ocean, these changes are also occurring in the distribution and abundance, phenology, demography, committee structure, physiological condition and calcification rates of Pacific Ocean organisms and ecosystems.

Our understanding of the pattern of changes that are occurring in the Indian Ocean suffers from a paucity of observational data, with a very low number of long-term observations (which are restricted to seabirds). This said, changes within the Indian Ocean show a close resemblance to that occurring in the Pacific and Atlantic oceans.

The semi-enclosed sees the world are undergoing rapid physical and chemical changes at rates which are several times that scene for oceans globally. These rapid rates of change have resulted in regime shifts, in which entire ecosystem assemblages change rapidly from one state to another.

As with the three ocean basins considered in this chapter, the world's semi-enclosed seas (Mediterranean Sea, Red Sea, Arabian Gulf, Baltic Sea, American Mediterranean sea- Gulf of Mexico and Caribbean Sea- and the Australasian Mediterranean sea) undergoing major biological reorganization. In a total of 174 published observations, 93% showed consistency with the expected direction under climate change. Many examples involved alien species moving into semi-enclosed seas as conditions changed, driving major changes to the assemblages.

Near term projections of change (up to 2050) are similar for low (RCP 2.6) and high (RCP 8.0) climate change scenarios and are largely indistinguishable. Physical and chemical changes are likely to continue and to be similar to those that have occurred over the last 50 years. Using this information, the average rate of warming of the ocean is likely to be around 0.24°C per decade. This could give the ocean is also likely to increase by a further 0.05-0.1 pH units.

Under these conditions, ocean ecosystems such as coral reefs, kelp forests and other coastal ecosystems are likely to experience increasing stress and loss. Rising sea levels will also impact coastal ecosystems such as mangroves and seagrass beds. Many of these systems will contract by as much as 50% over the next 40 years.

Given the current rates of range extension (49.2 ± 5.6 km per decade), many marine organisms will extend their distribution by an average of 200 km to higher latitudes, with the subsequent contraction of the ranges of lower latitudes. Similarly, the changes in the timing of biological events such as spawning and migration will change by around 20 days by 2050.

The changes to the biology of the ocean up to 2050 will diminish many of the ecosystem services that are currently enjoyed by human communities and industries within the global ocean. Projections of change beyond 2050 a difficult due to the scale of changes currently occurring within the ocean. RCP 2.6, where atmospheric CO2 peaks at 490 ppm and declines as the century ends represents a scenario in which marine ecosystems will change their nature and geographic spread, and in which adaptation strategies have some degree of likelihood of working. A key property of RCP 2.6 is that the rate of environmental change will diminish, allowing many ecosystems to redistribute themselves according to their temperature requirements. Under RCP 4.5, 6.1 and 8.0, the likelihood of marine ecosystems persisting in any shape or form that is similar to today is reduced substantially.

Key sectors such as marine related fishing and tourism are perceived to be highly vulnerable and at risk as ecosystem changes change the dominant fish species within regions, and the quality of tourist destinations associated with oceanic and coastal areas. Shipping (transport) and oil and gas extraction are less likely to be affected, although extreme events have proved to be highly damaging to their operation within areas such as the Gulf of Mexico.

30.12.2. Emerging Themes

Dissolved oxygen concentrations are declining at many sites within 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 respiration to photosynthesis. The decline in oxygen concentrations in large parts of the ocean is of great concern to oceanographers given the ramifications for marine species and ecosystems.

Ocean acidification in response to the rising concentration of carbon dioxide has pushed the chemistry of the ocean outside where it's been for at least 1 million years. At current rates of increase in the atmosphere, the acidity of the ocean will surpass any scene over the last 40 million years. This represents a major change to the chemistry of the oceans, and there is a growing literature documents a major array of changes from restricting the calcification of coral reefs and important pelagic organisms such as pteropods, to interfering with animal reproduction and olfactory systems. Ocean acidification is emerging as a very serious issue for all ocean regions, although the greatest impacts of changing pH and carbonate ion concentrations are being felt at higher latitudes due to the cold temperature and the greater flux of CO2 entering these waters.

30.12.3. Research and Data Gaps

Changes in the chemical composition of the ocean, particularly oxygen will require further attention given the enormity of their importance to the biology of the planet. These studies must be expanded geographically and must include occur at a finer scale than currently. Only by gaining this information, will we be able to distinguish long-term trends associated with climate change from intra-and inter annual variability.

A range of research and data gaps exist and currently inhibit progress toward understanding the impacts of climate change on the world's oceans. While the number of studies focused on how on marine ecosystems are responding to climate change has increased substantially over the past decade, much of this work 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 nature (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 which will require an expansion of the focus of future studies to include these organisms, which are often crucial within ocean ecosystems and processes.

Changes in primary productivity in the open ocean will require additional attention, especially given the large-scale trends that have been occurring in the Pacific and Atlantic oceans. We currently do not have an effective handle on how these changes are going to play out as further warming and acidification occurs. Given that 50% of the primary production of the planet comes from marine ecosystems, understanding these patterns of change must be a priority.

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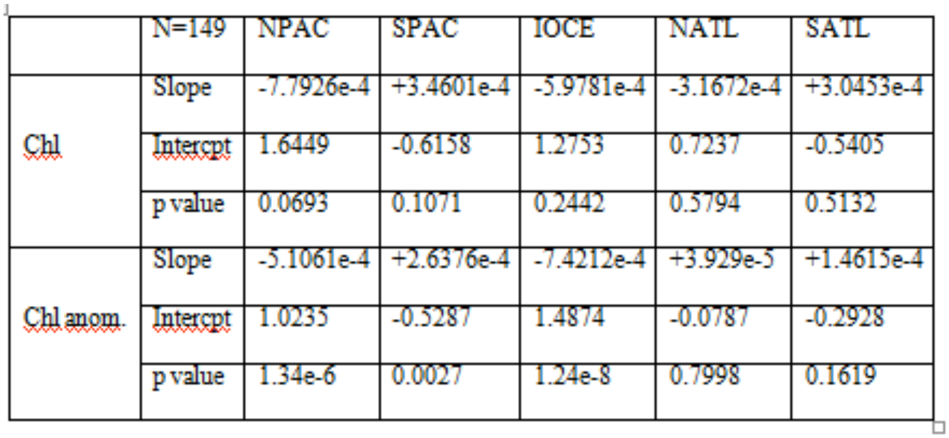
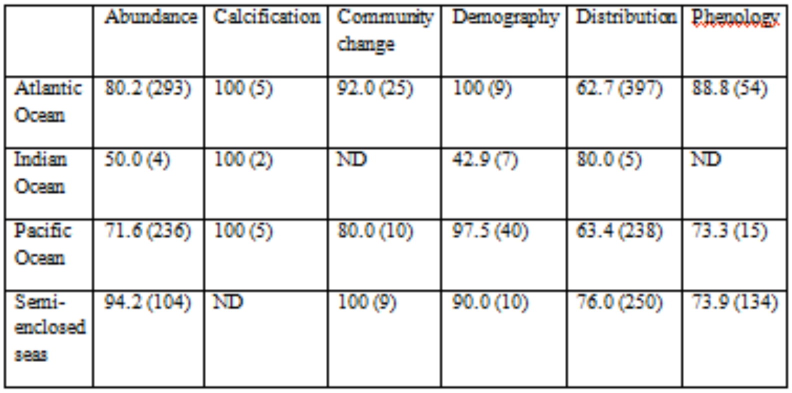
Table 30-1: Linear trends of averaged Chl and Chl anomaly for all five gyres.



	N=149	NPAC	SPAC	IOCE	NATL	SATL
Chl	Slope	-7.7926e-4	+3.4601e-4	-5.9781e-4	-3.1672e-4	+3.0453e-4
	Intercpt	1.6449	-0.6158	1.2753	0.7237	-0.5405
	p value	0.0693	0.1071	0.2442	0.5794	0.5132
Chl anom.	Slope	-5.1061e-4	+2.6376e-4	-7.4212e-4	+3.929e-5	+1.4615e-4
	Intercpt	1.0235	-0.5287	1.4874	-0.0787	-0.2928
	p value	1.34e-6	0.0027	1.24e-8	0.7998	0.1619

Table 30-2: Proportion of responses (%) consistent with climate change in each ocean region by observation type. Total number of observations given in brackets. ND= no data.



	Abundance	Calcification	Community change	Demography	Distribution	Phenology
Atlantic Ocean	80.2 (293)	100 (5)	92.0 (25)	100 (9)	62.7 (397)	88.8 (54)
Indian Ocean	50.0 (4)	100 (2)	ND	42.9 (7)	80.0 (5)	ND
Pacific Ocean	71.6 (236)	100 (5)	80.0 (10)	97.5 (40)	63.4 (238)	73.3 (15)
Semi-enclosed seas	94.2 (104)	ND	100 (9)	90.0 (10)	76.0 (250)	73.9 (134)

BACKGROUND FOR SECTION 30.4

TO BE REMOVED - Table 1, Moss et al. (2010)

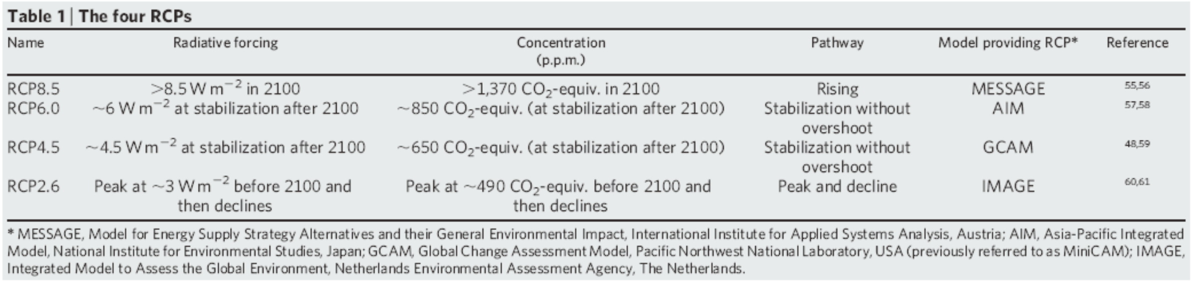


Table 1 | The four RCPs

Name	Radiative forcing	Concentration (p.p.m.)	Pathway	Model providing RCP*	Reference
RCP8.5	>8.5 W m^{-2} in 2100	$>1,370$ CO_2-equiv. in 2100	Rising	MESSAGE	55,56
RCP6.0	~6 W m^{-2} at stabilization after 2100	~850 CO_2-equiv. (at stabilization after 2100)	Stabilization without overshoot	AIM	57,58
RCP4.5	~4.5 W m^{-2} at stabilization after 2100	~650 CO_2-equiv. (at stabilization after 2100)	Stabilization without overshoot	GCAM	48,59
RCP2.6	Peak at ~3 W m^{-2} before 2100 and then declines	Peak at ~490 CO_2-equiv. before 2100 and then declines	Peak and decline	IMAGE	60,61

* MESSAGE, Model for Energy Supply Strategy Alternatives and their General Environmental Impact, International Institute for Applied Systems Analysis, Austria; AIM, Asia-Pacific Integrated Model, National Institute for Environmental Studies, Japan; GCAM, Global Change Assessment Model, Pacific Northwest National Laboratory, USA (previously referred to as MiniCAM); IMAGE, Integrated Model to Assess the Global Environment, Netherlands Environmental Assessment Agency, The Netherlands.

Table 30-3: Summary of first observations of species from the Atlantic Ocean where authors have suggested that climate change has played a role. *Note that there are many instances of first observations in the literature but authors have not suggested possible reasons for the new observation and these particular papers have not been included here*.

Region	**Group**	**Species**	**Common name**	**Reference**	**Notes**
Icelandic waters (EEZ)	Fish	25 fish species		[*Astthorsson and Palsson*, 2006]	Not previously recorded by fisherman or researchers in this heavily fish area. Warmer water species moving north
Cantabrian Sea, Northern Spain	Fish	*Megalops atlanticus*	tarpon	[*Arronte et al.*, 2004]	Subtropical fish species that has previously only been recorded as far north as Portugal
Galician waters, Spain	Fish	*Physiculus dalwigki* *Neoscopelus microchir* *Gaidropsarus granti* *Pisodonophis semicinctus*		[*Banon*, 2004; *Banon and Sande*, 2008; *Banon et al.*, 2002; *Bañón and Sande*, 2007]	New northern limit in the North Atlantic
Galician waters, Spain	Fish	*Lepidotrigla dieuzeidei* *Kyphosus sectatrix*		[*Banon*, 2004]	Tropical species found south of Portugal
British waters	Fish	*Zenopsis conchifer*	Sailfin dory	[*Swaby and Potts*, 1999]	Movement north into British waters
Rockall Trough, west of Ireland	Fish	19 fish species		[*Byrkjedal et al.*, 2004]	Mesopelagic southern temperate and subtropical species
Mar del Plata, Argentina	Fish	*Aluterus scriptus*	Scrawled filefish	[*Byrkjedal et al.*, 2004]	Tropical species
Falkland Islands	Fish	*Nemadactylus bergi*	morwong	[*Anders*, 2010]	Subtropical species to 45oS previously
Gulf of Cadiz, Spain	Fish	*Chloroscombrus chrysurus*	Atlantic bumber	[*Acosta et al.*, 2009b]	Previously only to 25oN off Mauritania
Southern Portugal	Fish	*Sparisoma cretense*	Mediterranean parrotfish	[*Abecasis et al.*, 2006]	
Chesapeake Bay, USA	Fish	*Trachinocephalus myops*	snakefish	[*Halvorson*, 2007]	Northerly extensions of distribution
		Citharichthys macrops	spotted whiff		
		Mullus auratus	red goatfish		
NW coast, Spain	Fish	*Alloteuthis africana*	NA	[*Guerra et al.*, 2002]	Previously northern limit off the western Sahara for *A. Africana*. Previously *C. hippos* only found as far north as Portugese waters
		Caranx hippos	Kingfish		
UK waters	Intertidal	*Solidobalanus fallax*	barnacle	[*Southward*, 1995]	Tropical species now found in western English Channel
Iceland	Crabs	*Cancer pagurus*	European edible crab	[*Galan and Eiríksson*, 2009]	New occurrences in Icelandic waters and represent large changes in distribution for *C. bellianus* (Azores) and *C. irroratus* (Nova Scotia)
		Cancer bellianus	toothed rock crab		
		Cancer irroratus	Atlantic rock crab		

Normandy, English Channel	Crabs	*Pachygrapsus marmoratus*	marbled crab	[*Dauvin*, 2009]	Warm-water species. Also recently sighted in southern coastal waters of UK (Ingle & Clark 2006)
Gulf of Cadiz, Spain	Scleractinian coral	*Dendrophyllia laboreli*		[*Lopez-Gonzalez et al.*, 2010]	Previously restricted to tropical waters between Ghana and Canary Islands. Could have been introduced by maritime traffic but colour morphology suggests natural expansion in distribution
Moray Firth, NE Scotland	Whale	*Ziphius cavirostris*	Cuvier's beaked whale	[*Robinson and MacLeod*, 2009]	Warm-water species not recorded previously from the North Sea
Galician coast, NW Spain	Mollusc	*Argonauta argo*	Paper nautilus	[*Guerra et al.*, 2002]	Previously only recorded off Lisborn (Portugal)
Galician coast, NW Spain	Whale	*Globicephala macrorhynchus*	Pilot whale	[*González et al.*, 2000; *Guerra et al.*, 2002]	First mass stranding of pilot whales in NE Atlantics

Table 30-4: Key vulnerabilities and risks for the world's oceans.

Schneider et al. (2007) Seven criteria identified for assessing key vulnerabilities (Ch19 WGII, AR4, IPCC)	Magnitude of impacts (scale: area, people affected and intensity: degree of damage caused). SCORE 1-5 (1 = small ... 5 = largest); 0 = unknown or not relevant.				Timing of impacts (a. sooner = more signficant; needs to consider 'delayed irreversibility') b. Rate at which it occurs and degree of non-linearity c. Impact on other vulnerabilities). SCORE 1-5 (1 = long-distant threat, 5 = immediate impact; 0 = unknown or not relevant.)				Persistence and reversibility of impacts (intensified recurrence e.g. 1000 year flood becomes decadal; also irreversibility) SCORE 1-5 (1 = low persistence and reversible, 5 highly persistant and irreversible; 0 = unknown or not relevant.)				Likelihood (estimates of uncertainty) of impacts and vulnerabilities and confidence in those estimates (likelihood of an outcome has been framed as the central value of a probability distribution, whereas confidence is reflected primarily by its spread). SCORE 1-5 (1 = not likely, 5 = highly likely; 0 = unknown or not relevant.)				Potential for adaptation (natural versus human systems). SCORE 1-5 (1= high adaptation potential; 5 = low adaptation potential (includes community change on ecosystems side ; 0 = unknown or not relevant.)				Distributional aspects of impacts and vulnerabilities (developing versus developed world; gender, age, cultural). SCORE 1-5 (1 = restricted impacts, 5 = broad set of people affected; 0 = unknown or not relevant.)				Importance of the system(s) at risk (highly subjective - e.g. Skiers value snow; different economic groups value different aspects unequally interms of value). SCORE 1-5 (1 = relatively unimportant, 5 = important to a wide number of people; 0 = unknown or not relevant).				
NATURAL SYSTEMS: AO: Atlantic Ocean and North Sea, PO: Pacific and Asian Seas, IO: Indian Ocean; Semi: Mediterranean Sea, Red Sea, Arabian Gulf, Baltic Sea, American Mediterranean sea (Gulf of Mexico and Caribbean Sea) and the Australasian Mediterranean sea.																													AVERAGE for issue
Vulnerability	AO	PO	IO	Semi	AO	PO	IO	Semi	AO	PO	IO	Semi	AO	PO	IO	Semi	AO	PO	IO	Semi	AO	PO	IO	Semi	AO	PO	IO	Semi	
Coastal ecosystems	4	4	4	4	5	5	5	5	4	4	4	4	4	4	4	4	3	3	3	3	4	4	4	4	5	5	5	5	4.1
Loss of habitat structuring species	5	5	5	5	5	5	5	5	4	4	4	4	4	4	4	4	3	3	3	3	3.5	3.5	3.5	3.5	4	4	4	4	4.1
Deoxygenation of core ocean and growing ocean anoxia	5	5	5	5	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	3	3	3	3	4	4	4	4	3.8
Exceedance of temperature tolerance (e.g. Coral reefs)	3	3	3	4	5	5	5	5	3	3	3	4	5	5	5	5	4	4	4	4	2.5	2.5	2.5	2.5	3	3	3	3	3.7
Distribution and abundance of species	5	5	5	5	5	5	5	5	3	3	3	4	4	4.5	4	4	2	2	2	2	2.5	2.5	2.5	2.5	3	3	3	3	3.6
Shifts in phenology	5	5	5	5	5	5	5	5	3	3	3	4	4	4.5	4	4	2	2	2	2	2.5	2.5	2.5	2.5	3	3	3	3	3.6
Antagonisms between local stressors and climate change	4	3	4	5	4	3	4	5	3	3	3	4	5	5	5	5	1	1	1	1	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Ocean acidification impacts on reproduction	4	4	4	4	2	2	2	2	3.5	3.5	3.5	5	4	3.5	4	4	4	4	4	4	3	3	3	3	3	3	3	3	3.4
Impacts of temperature on larval development and timing.	4	4	4	4	3	3	3	3	3	3	3	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3.3
Reduced marine calcification	3	3	3	3	2	2	2	2	3.5	3.5	3.5	5	4	4	4	4	4	4	4	4	2	2	2	2	3	3	3	3	3.1
Changes in demography, community structure and condition	4	4	4	4	4	4	4	4	3	3	3	4	4	4	4	4	1	1	1	1	2.5	2.5	2.5	2.5	3	3	3	3	3.1
Changing ocean current direction and strength	3	3	3	3	2	2	2	2	3	3	3	4	3	3	3	3	4	4	4	4	2	2	2	2	3	3	3	3	2.9
Pelagic fish populations	2	2	2	2	3	3	3	3	3	3	3	4	4	4	4	4	1.5	1.5	1.5	1.5	3	3.5	3.5	3.5	2.5	3	3	3	2.9
Productivity of ocean gyres	4	4	4	2	4	4	4	0	3.5	3.5	3.5	0	3	3	3	0	2	2	2	5	2	2	2	2	3.5	3.5	3.5	3.5	2.8
HUMAN SYSTEMS AND INDUSTRIES: AO: Atlantic Ocean and North Sea, PO: Pacific and Asian Seas, IO: Indian Ocean; Semi: • Mediterranean Sea, Red Sea, Arabian Gulf, Baltic Sea, American Mediterranean sea (Gulf of Mexico and Caribbean Sea) and the Australasian Mediterranean sea.																													
Vulnerability	IO	PO	AO	Semi	IO	PO	AO	Semi	IO	PO	AO	Semi	IO	PO	AO	Semi	IO	PO	AO	Semi	IO	PO	AO	Semi	IO	PO	AO	Semi	
Tourism	3	3	3	3	4	4	4	4	3.5	3.5	3.5	4	4	5	4	5	2	2	2	1	3	3	3	4	3	4	3	4	3.4
Fisheries	2	2	2	2	3	3	3	3	3	3	3	4	4	4	4	4	1.5	1.5	1.5	1	3	3	3	3	3.5	3.5	3	3.5	2.9
Shipping	1	1	1	1	2	2	2	2	3	3	3	4	2	2	2	2	1	1	1	1	3.5	3.5	3.5	3	3	3	3	2	2.2
Gas and Oil recovery	2	2	2	2	3	3	3	3	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	2	2	2	2	1.9

Table 30-5: (A) Potential mitigation options for international shipping, and (B) potential implications of adaptation in maritime transport (UNCTAD, 2009).]

A

Scope of intervention	**Measure**	**Example**
Technology & Energy	• Efficient and lower-emitting propulsion systems • Clean fuels and alternative energy sources • Ship design (structure, hull and machinery) • • Emission control technologies (e.g. after exhaust treatment, carbon captures and storage)	• EU and IMO sulfur emission control areas • Solar Sailor 2006 and Skysails 2006 • • Switch from diesel to natural gas
Operational	• Speed Reduction • Route selection • Monitoring of weather and sailing conditions • Collaboration among ports, carriers, other modes and other players in the supply chain • • Cold ironing or onshore power	• NYK announcement in early 2008 to reduce the speed of all vessels in the fleet by 10% to cut fuel consumption by up to 25% • • Vessel sharing agreement between Maersk MSC and CMA-CGM on Transpacific trade
Market-based	• Environmentally differentiated rates/dues • Cap and trade • Taxation • Subsidies • • Industry-led voluntary schemes	• Fairway dues in Sweden, Green Award Scheme, Green Shipping Bonus, differentiated tonnage tax in Norway • Kyoto CDM and JI • EU ETS and proposed IMERS • Potential global fuel tax • California Air Investment Programme • • Preferential contracting

B

Climate change factor	**Potential implications**	**Adaptation measures**
Rising temperatures • High temperatures • Melting ice • Large variations (spatial and temporal) • Frequent freeze and thaw cycles	• Longer shipping season (NSR), new sea route (NWP) • Shorter distance for Asia–Europe trade and less fuel consumption • Additional support services and navigation aids such as ice-breaking search and rescue • Competition, lower passage tolls and reduced transport costs • New trade, diversion of existing trade, structure and direction of trade (indirectly through impact on agriculture, fishing and energy) • Damage to infrastructure, equipment and cargo • Increased construction and maintenance costs; new ship design and strengthened hulls; environmental, social, ecosystem related and political considerations • Higher energy consumption in ports • Variation in demand for and supply of shipping and port services • • Challenge to service reliability	• Heat-resistant construction and materials • Continuous inspection, repair and maintenance • Monitoring of infrastructure temperatures • Reduced cargo loads, speed and frequency of service • Refrigeration, cooling and ventilation systems • Insulation and refrigeration • Modal shift • Transit management scheme and regulation of navigation in northern regions • • Ship design, skilled labour and training requirements

Rising sea levels Flooding and inundation Erosion of coastal areas	• Damage to infrastructure, equipment and cargo (coastal infrastructure, port-related structures, hinterland connections) • Increased construction and maintenance costs, erosion and sedimentation • Relocation and migration of people and business, labour shortage and shipyard closure • Variation in demand for and supply of shipping and port services (e.g. relocating), modal shift • Structure and direction of trade (indirectly through impact on agriculture, fishing, energy) • Challenge to service reliability and reduced dredging, reduced safety and sailing condition	• Relocation, redesign and construction of coastal protection schemes (e.g. levees, seawalls, dikes, infrastructure elevation) • Migration • • Insurance
Extreme weather conditions Hurricanes Storms Floods Increased precipitation • Wind	Damage to infrastructure, equipment and cargo (coastal infrastructure, port-related structures, hinterland connections) Erosion and sedimentation, subsidence and landslide Damage to infrastructure, equipment, cargo Relocation and migration of people and business Labour shortage and shipyard closure Reduced safety and sailing conditions, challenge to service reliability Modal shift, variation in demand for and supply of shipping and port services • Change in trade structure and direction	Integrate emergency evacuation procedures into operations Set up barriers and protection structures Relocate infrastructure, ensure the functioning of alternatives routes Increase monitoring of infrastructure conditions Restrict development and settlement in low-lying areas Construct slope-retention structures Prepare for service delays or cancellations Strengthen foundations, raising dock and wharf levels Smart technologies for abnormal events detection • New design for sturdier ship

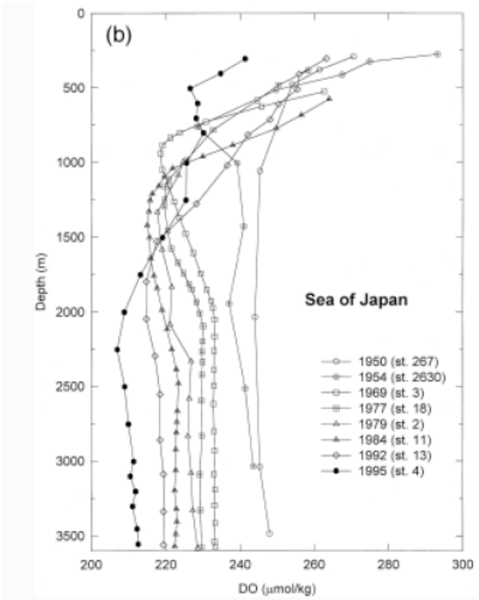
Table 30-6

Topic	**Brief Description**	**Impact**	**References**
Ocean storage by direct injection	Capture of CO_2 post-combustion from a power plant, followed by injection of liquid CO_2 by pipeline or from a ship into the deep ocean. Technology only practical for power plants situated in coastal regions.	Will add to ocean acidification and create localized harm to marine life. CO_2 capture is expensive. Quantities will be small relative to the atmospheric invasion signal. CO_2 injected will dissolve and be transported by ocean circulation with eventual surface exposure.	Caldeira, K., M. Akai, P. Brewer, B. Chen, P. Haugan, T. Iwama, P. Johnston, H. Kheshgi, Q. Li, T. Ohsumi, H. Poertner, C. Sabine, Y. Shirayama, and J. Thomson, 2005. Ocean Storage. In: (B. Metz and O. Davidson, eds.) Carbon Dioxide Capture and Storage: A Special Report of IPCC Working Group III, Cambridge University Press, Cambridge UK.
Sub-sea geologic storage	Capture of CO_2 from extracted gas or from post-combustion followed by well injection into a porous submarine aquifer beneath impermeable geologic strata.	Extensive experience in place from the Norwegian Sleipner field activity in the North Sea. CO_2 capture costs from extracted gas are less than from post-combustion. No evidence of ocean impact from leakage to date.	Benson, S., Cook, P. and 31 others, 2005. Underground Geological Storage. In: (B. Metz and O. Davidson, eds.) Carbon Dioxide Capture and Storage: A Special Report of IPCC Working Group III, Cambridge University Press, Cambridge UK.
Iron Fertilization	Spreading of trace amounts of reduced iron over very large areas of the surface ocean where excess nutrients occur. Overcoming the local iron deficiency creates extensive phytoplankton blooms drawing down sea surface pCO_2.	Much of the exported organic matter is remineralized at shallow depths creating local oxygen stress and shallow CO_2 enrichment. The effects are temporary and the effective retention time is short. Relatively low cost procedure.	Boyd, P.W. and 22 others, 2007. Mesoscale iron enrichment experiments 1993-2005: Synthesis and future directions. Science, 315, 612-617.
Carbonate neutralization	Dissolution of power plant flue gas into sea water yielding an acidic solution which is neutralized by addition of crushed limestone. The resulting bicarbonate rich fluid is discharged to the ocean.	Involves the transport and crushing to fine scale of large quantities of limestone and the processing of very large quantities of sea water. Relatively low cost. Environmental impact issues related to discharge not yet explored.	Rau, G.H., 2011. CO2 mitigation via capture and chemical conversion in sea water. Environ. Sci. Technol., 45, 1088-1092.
Accelerated olivine weathering	Uses wind powered electrochemical processes to remove HCl from the ocean and neutralizes the acid with silicate minerals such as olivine for disposal. The net result is to add alkalinity to the ocean akin to natural silicate weathering processes.	Complex system as yet untested in pilot processes. Involves mining and crushing large quantities of silicate minerals. Very long time scale consequences uncertain.	House, K.Z., House, C.H., Schrag, D.P., and Aziz, M.J., 2007. Electrochemical acceleration of chemical weathering as an energetically feasible approach to mitigating anthropogenic climate change climate change. Environ. Sci. Technol., 41, 8464-8470.
Kinetic energy extraction	Direct extraction of energy from ocean currents and waves	Tested in pilot forms on tidal streams. Energy available is proportional to velocity cubed, and rotors are located close to the surface layers where velocity is highest. Very strong forces on the structure requires heavy engineering.	Douglas, CA, Harrison, G.P., and Chick, J.P., 2008. Lifecycle assessment of the Seagen marine current turbine. Proc. IMechE, 222, 1-12.

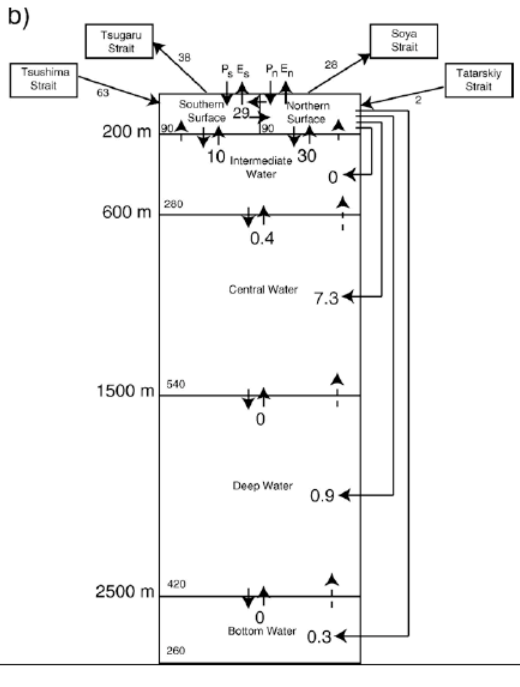
Box 30-1

Dissolved Oxygen Trends in a Marginal Sea - Japan/East Sea

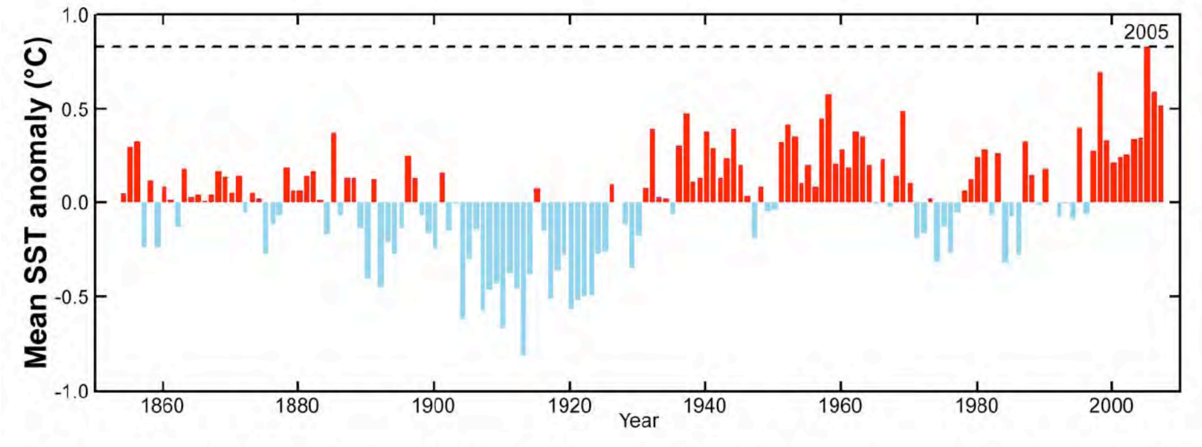
One of the best documented cases of oceanic oxygen declines related to climate change is that of the deep waters of the Japan/East Sea. In Figure xx we show the observed trends in deep water O_2 (Chen et al., 1999) and below that a model of the processes at work (Jenkins, 2008).



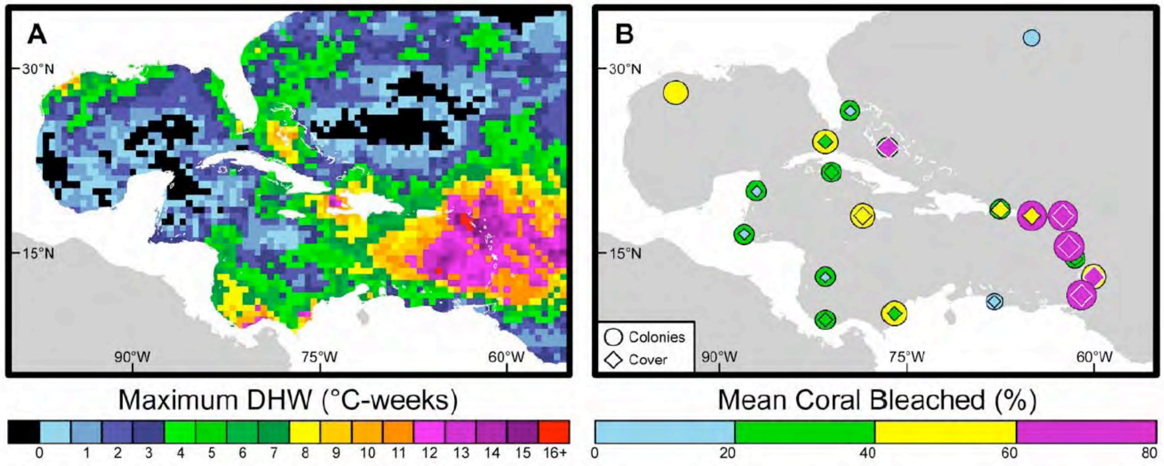
Time trends of dissolved oxygen in the Japan Sea driven by decreasing water mass renewal. Observations extend over 50 years and show O_2 levels declining at 0.007 μmol/kg/yr leading to prediction of a fully anoxic basin by the year 2200. The increasing stagnation of the deep waters is consistent with recent climate change scenarios, but the decline very likely began before 1950. The observed small increase in deep water temperatures partly attributable to heat flow through the sediments. Periodic deep water renewal events from extremely cold winters can occur. This is not frequent enough to overcome the general decline in O_2.



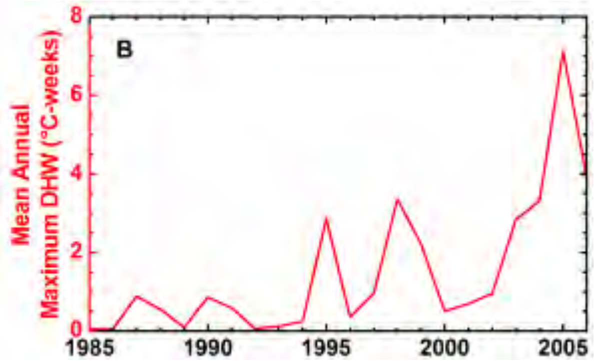
A box model simulation of time trends of biogeochemical properties in the Japan/East Sea calibrated with geochemical tracer data. Paired arrows indicate exchanges between boxes, long arrows (right) are water mass formation rates, both in units of 10^{12} m^3 per year. The result shows a nearly 10-fold decrease in deep water formation rates over the period and a nearly 2-fold decrease in new primary production as lesser quantities of nutrients are returned to the surface waters. The decline in water mass formation rates is associated with reduced ice formation and brine rejection in the critical deep water formation areas.



Box Figure 1: Long-term temperature records from the Caribbean Sea. Temperature anomalies (2.0° x 2.0° pixels) were computed relative to the mean sea temperature (1901-2000) using the NOAA Reconstructed Sea Surface Temperature data set (ERSST). Used with permission from Eakin et al. 2010.

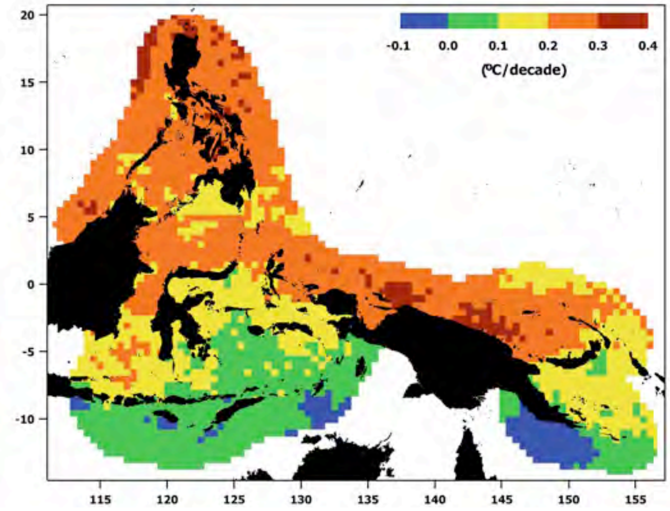


Box Figure 2: A. Accumulated heat stress calculated (0.5° x 0.5° pixels) as Degree Heating Week (DHW, Liu et al. (2006)). Generally, values greater than 4°C- weeks generally results in significant bleaching while 8°C-weeks generally results in widespread bleaching and mortality. B. Jurisdictional means of Coral bleached; marker colour and size indicates severity as measured by either the percent of live coral colonies bleached (circles), or the percent of coral cover bleached (diamonds). Areas in the eastern Caribbean lost as much as 40% of their coral colonies following almost complete 80% of their coral communities bleached. Used with permission from Eakin et al. 2010.



Box Figure 3: Average of annual maximum thermal stress (DHW) values at reef bearing pixels in the greater Caribbean Sea region during 1985–2006. See Eakin et al 2010 for description of methods and geographic area. Significant coral bleaching was reported during periods with average thermal stress above 0.5°C-weeks, and was especially widespread in 1995, 1998, 2005, and 2010. Used with permission after Eakin et al. 2010 with addition of data for years 2007-2010.

Box Figure 4: The Coral Triangle includes 6.8 km^2 of ocean territory and 132,000 km of coastline. The boundaries to the Coral Triangle are based on high levels of marine biodiversity.



Box Figure 5: Trends in sea temperature (0.5° x 0.5° pixels) for the period 1985 to 2006 as calculator from biweekly satellite data collected by the National Oceanic and Atmospheric Administration in Washington DC.

Figure 1

Place holder - (Needs to be replaced by the appropriate reference and summary datasets from WG1 CH3): (a) Average annual sea surface temperature, (b) surface salinity; (c) pH of the global ocean, and (d) change in carbonate ion concentration since the beginning of the industrial revolution. If possible have maps extend from Africa to Africa in order to keep three ocean basins clearly visible and intact. Need to get appropriate and referenced figures from WG1

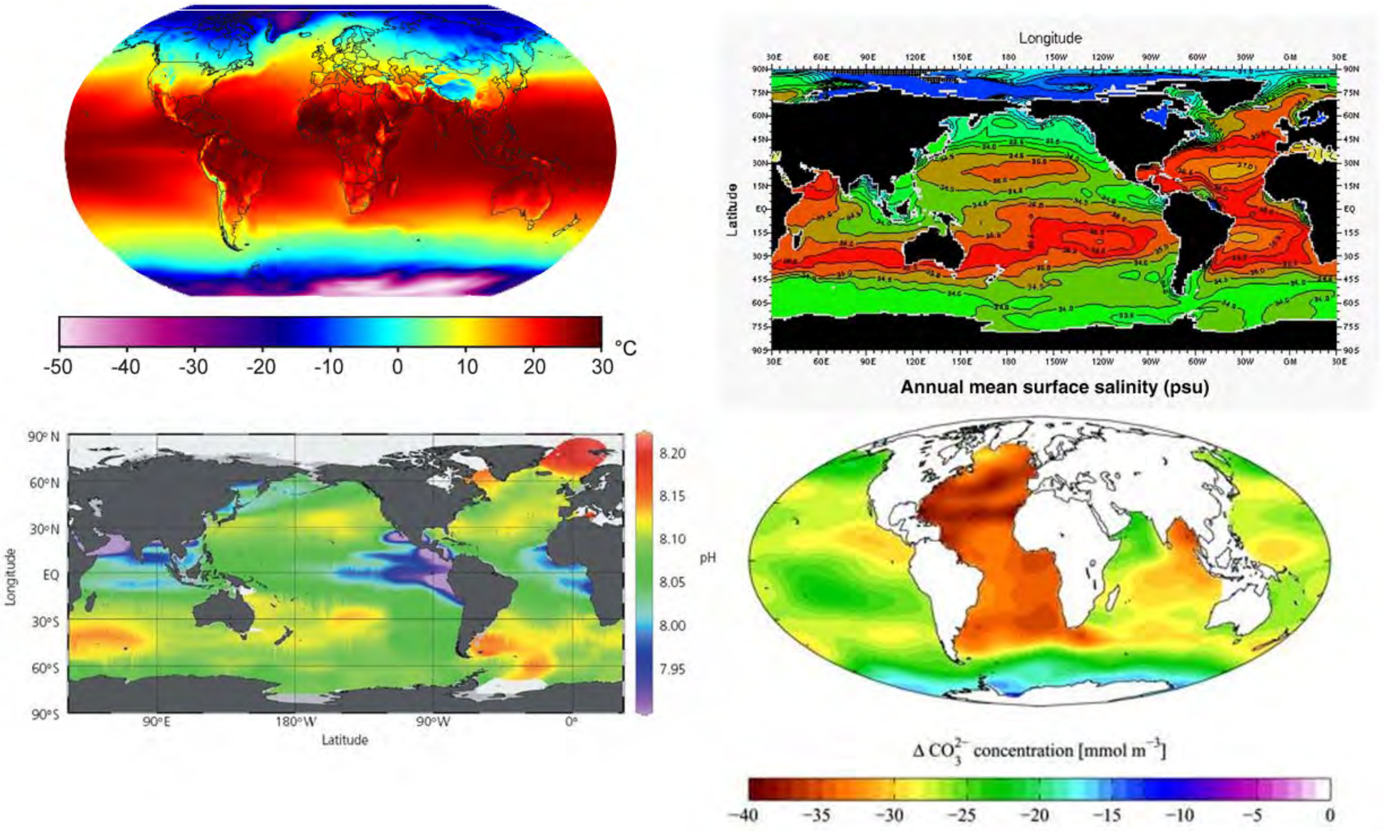


Figure 2

PLACE-MARKER FIGURE: Major currents ... something like these ... shaded regions represent areas covered in chapter 30 - again tries to be consistent with figure 1 - Africa to Africa orientation. Possibly with ocean gravity-large scale sea floor features as base map – get artist to make this figure eventually)

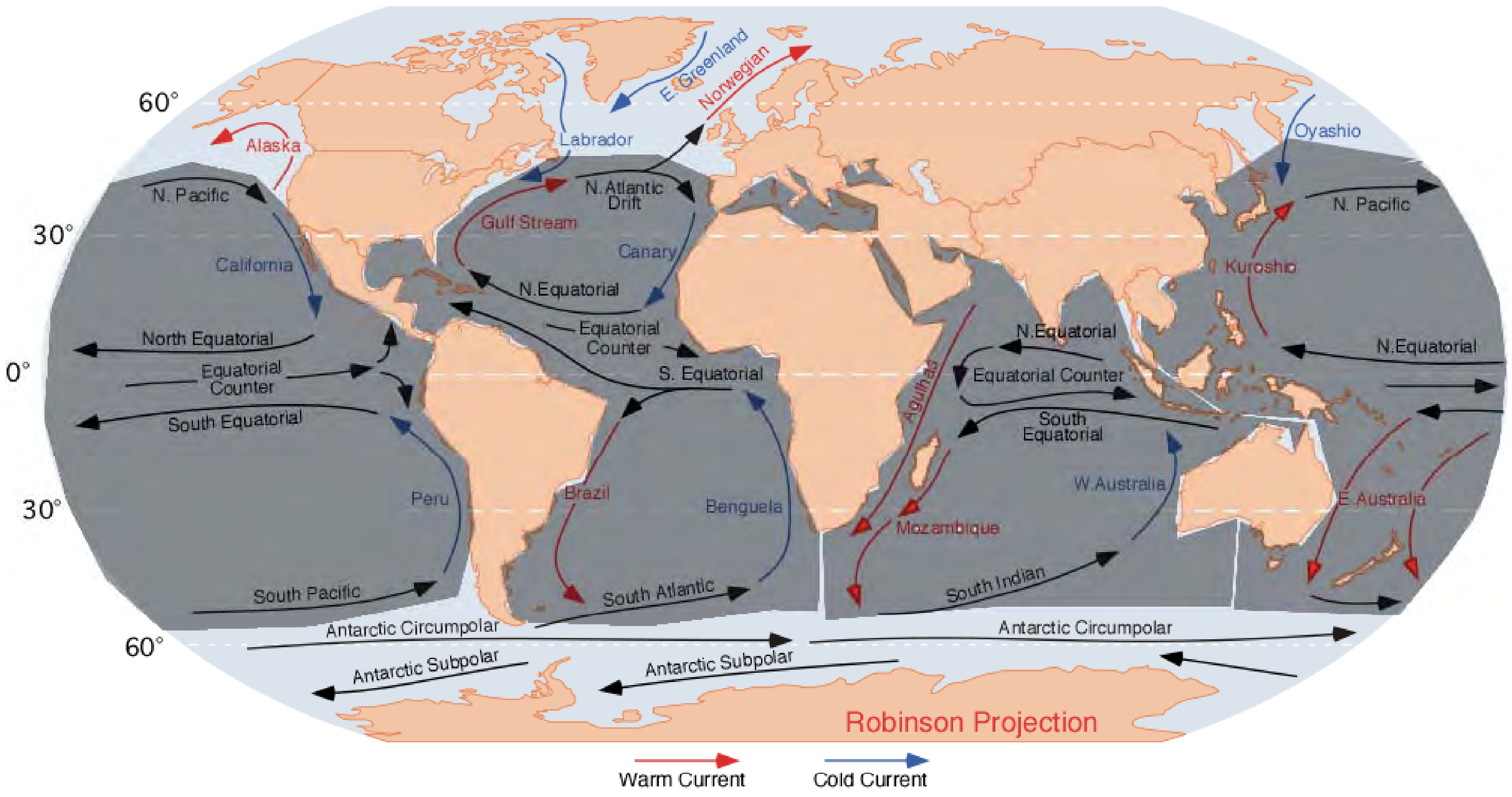


Figure 3

Global annual primary production (gC m^{-2} yr^{-1}). Total estimated production is 104.9 $x10^{15}$ g C yr^{-1} of which 46.2 % in the ocean. After Field *et al.* (1998).

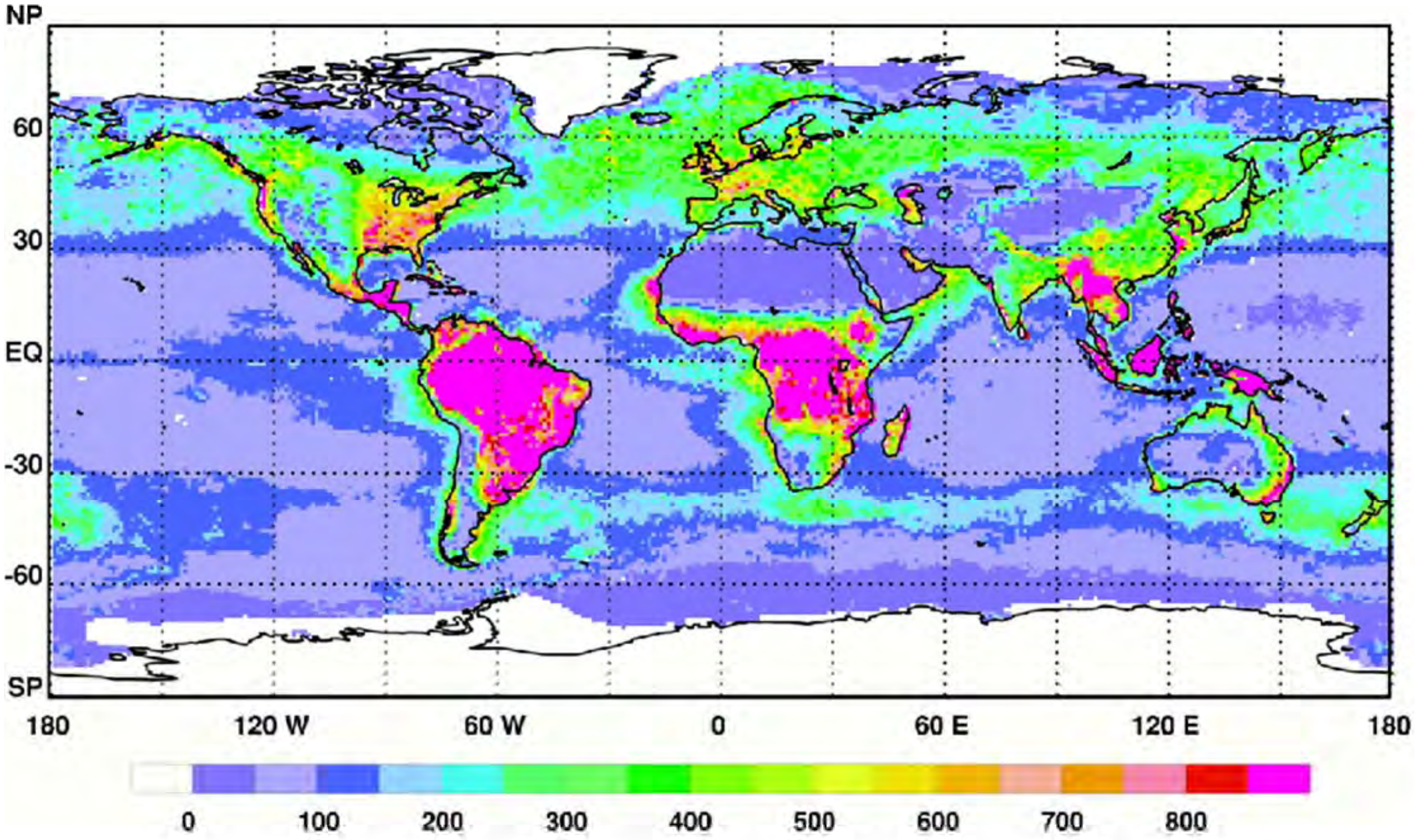
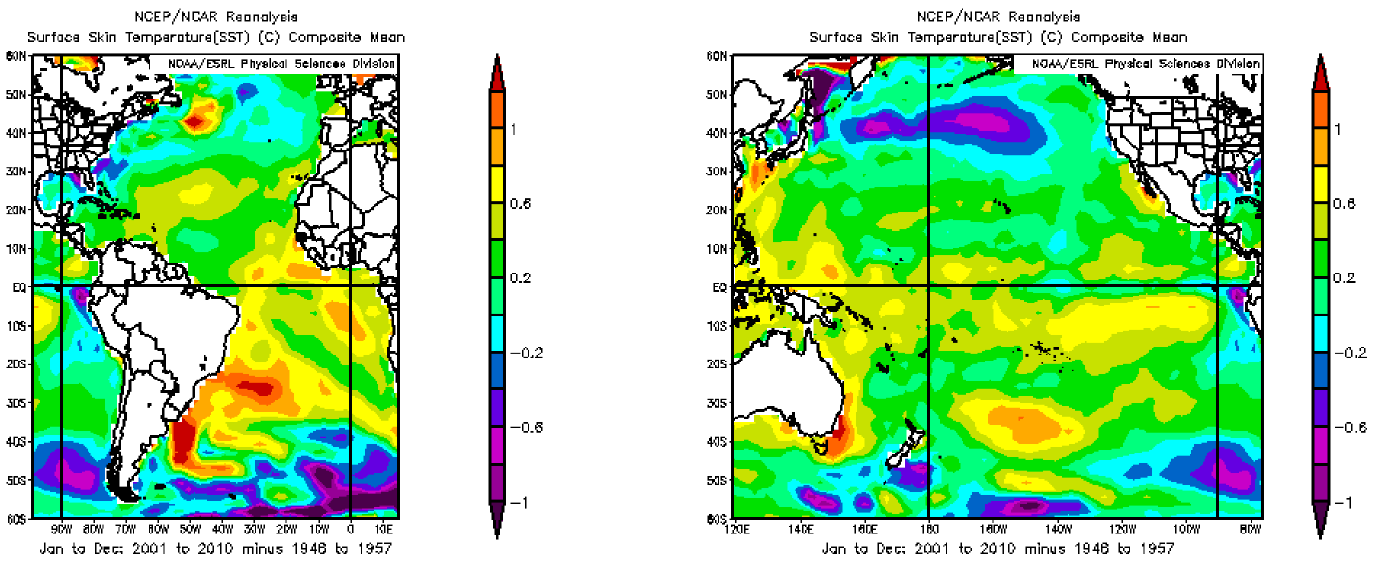
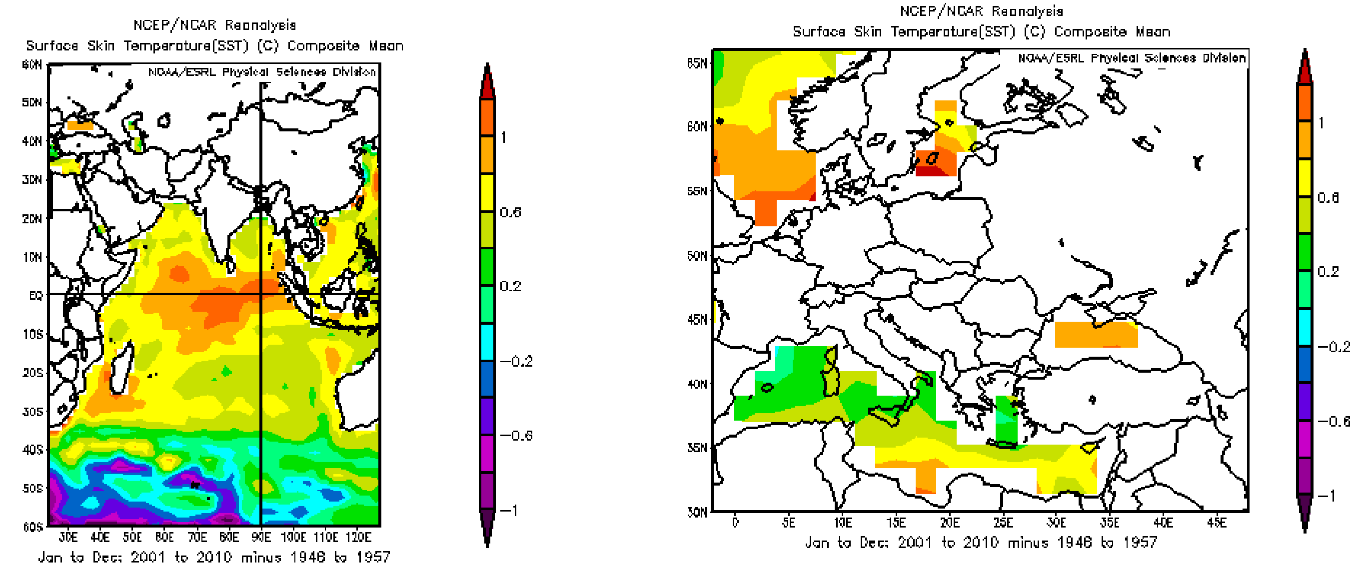


Figure 4A Changes in sea surface temperature (2010-2001 relative to 1948-1957)



A. Atlantic Ocean and Caribbean Sea

B. Pacific Ocean and South-east Asian seas



C. Indian Ocean, Arabian Gulf and Red Sea

D. North, Baltic and Mediterranean Seas

Figure 4B

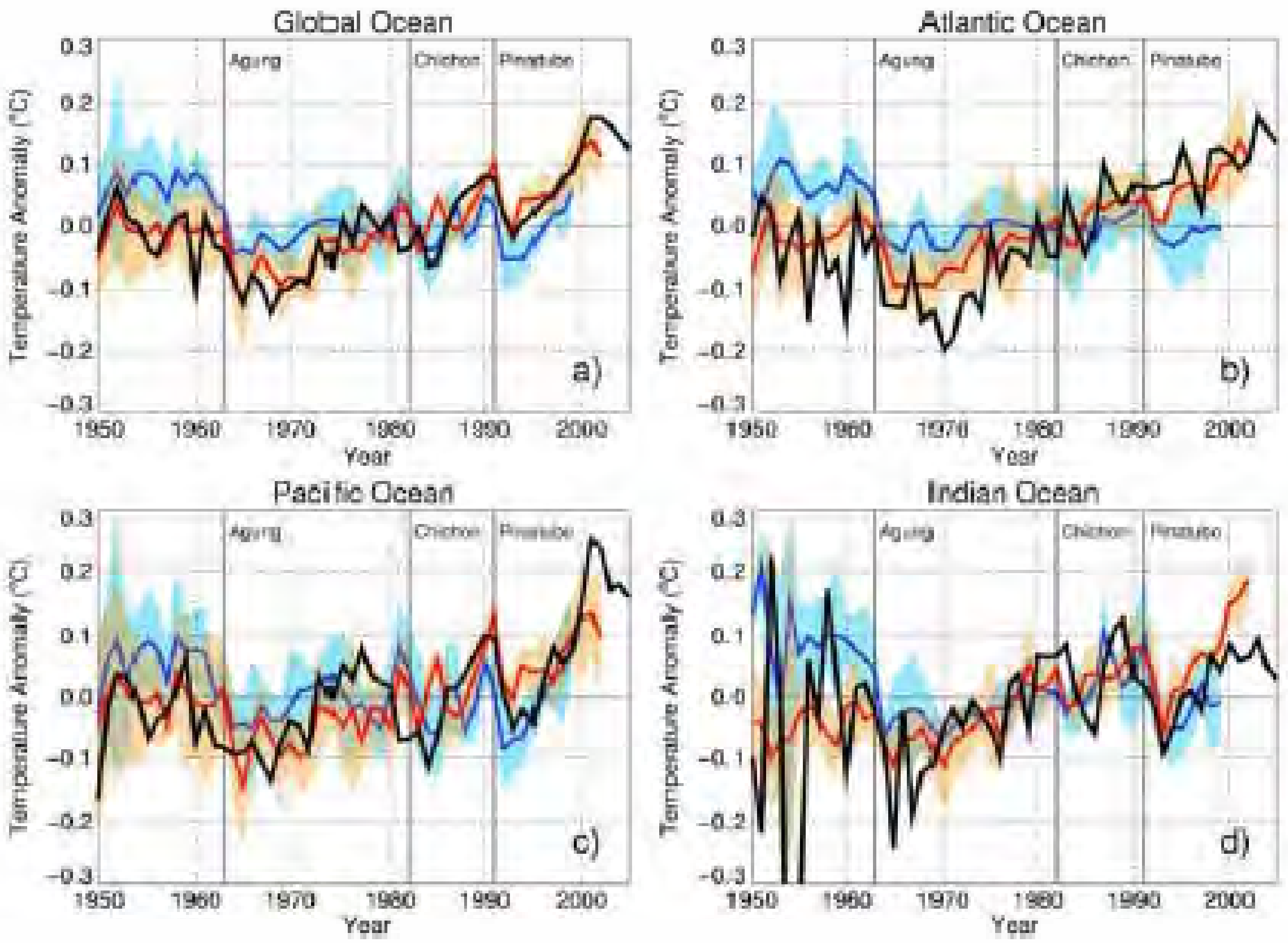
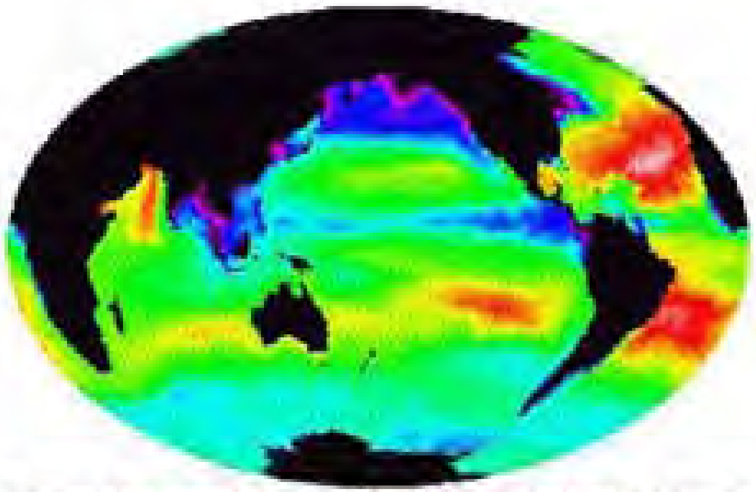
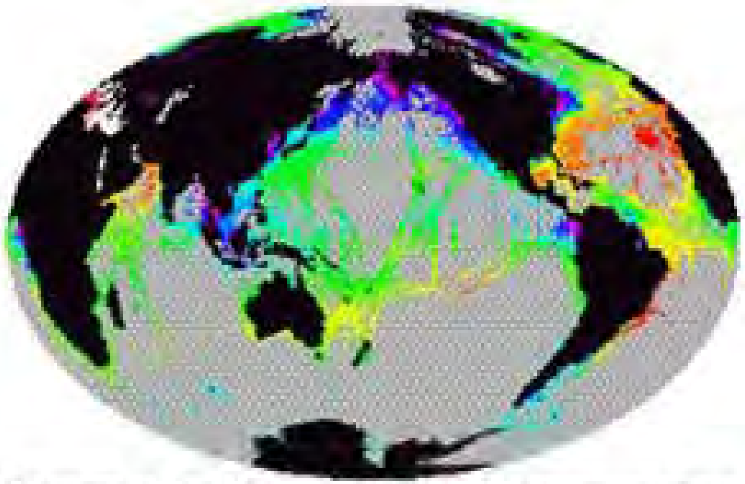


Figure 1. Time series of global ocean temperature above 220 m (T_{220m}) relative to 1950–1999 average, for (a) Global Ocean, (b) Atlantic Ocean (c) Pacific Ocean, and (d) Indian Ocean. Shown are: the XBT-corrected observations (black); the HadCM3 ALL ensemble average (red) and ensemble standard deviation (orange shading); and the HadCM3 NAT ensemble average (blue) and ensemble standard deviation (light blue shading). The model data have been re-gridded and sub-sampled to match the observational coverage. The vertical lines show the approximate timing of the major volcanic eruptions.

Figure 4C

Ocean salinity: comparison of today with 100 years of measurements

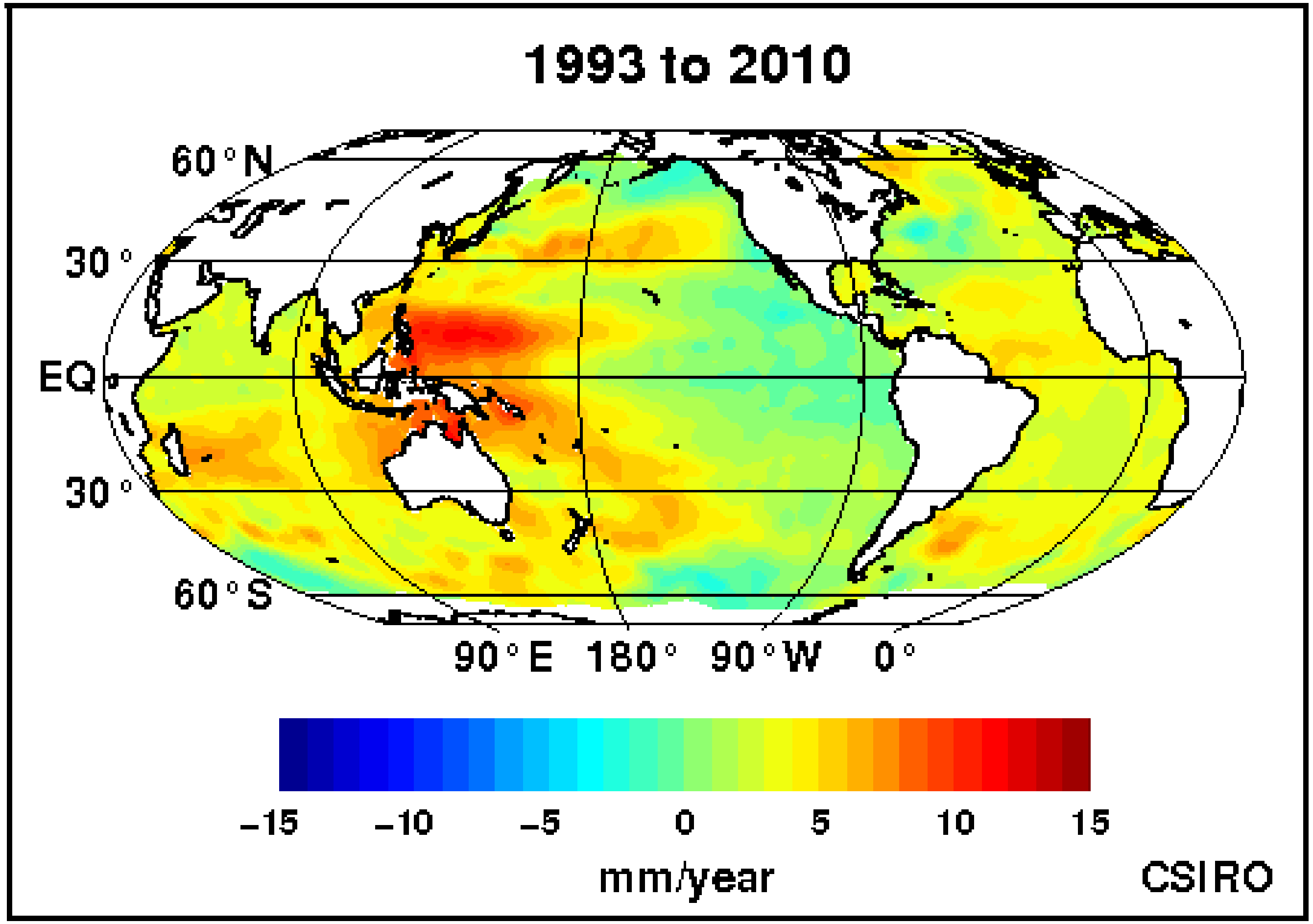

Example 8 days of Aquarius Sea Surface Salinity (SSS) data


100 years of Sea Surface Salinity (SSS) measurements

Place holder – Will Skirving – NOAA - investigating

Figure 4D

Changes in sea level: 2010 relative to 1993
(NOAA Laboratory for Satellite Altimetry)



See e-mail by John Church – May 17
http://www.cmar.csiro.au/sealevel/sl_hist_last_15.html

Figure 5A

Ocean pH as a function of atmospheric carbon dioxide concentration

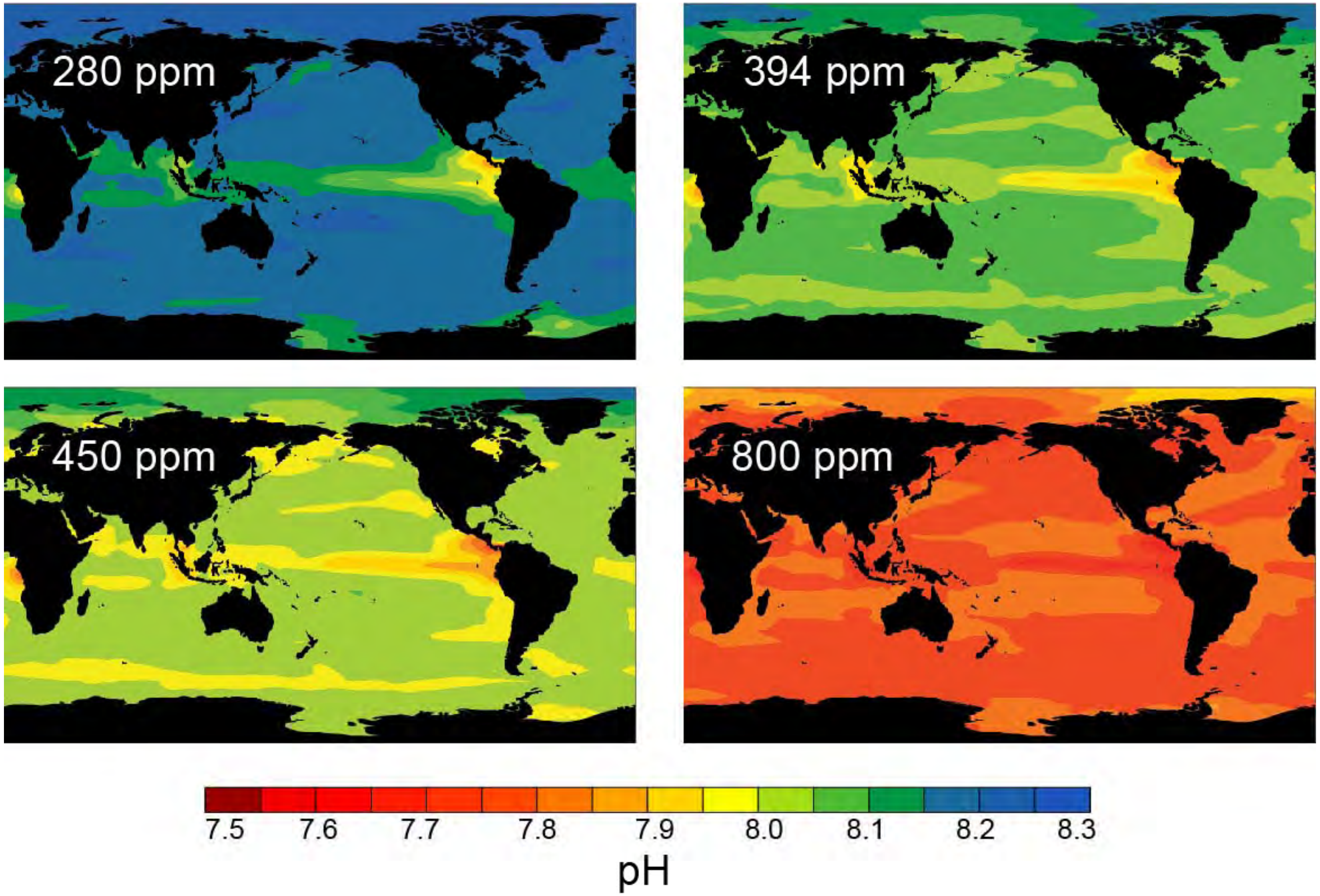


Figure 5B

Aragonite saturation as a function of atmospheric carbon dioxide concentration

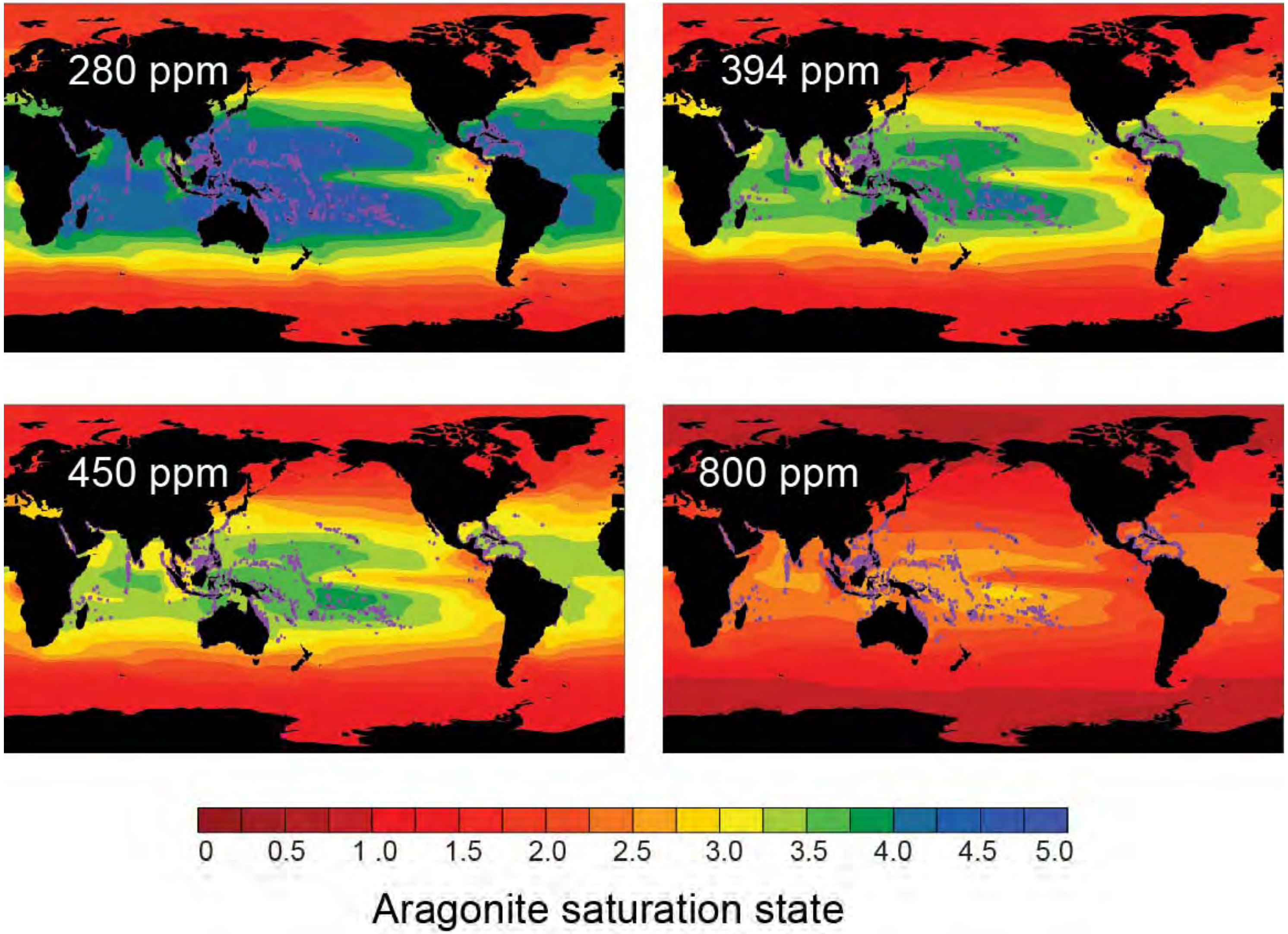


Figure 5C

Carbon dioxide flux and carbon storage is a function of atmospheric carbon dioxide concentrations (change relative to those at 280 ppm)

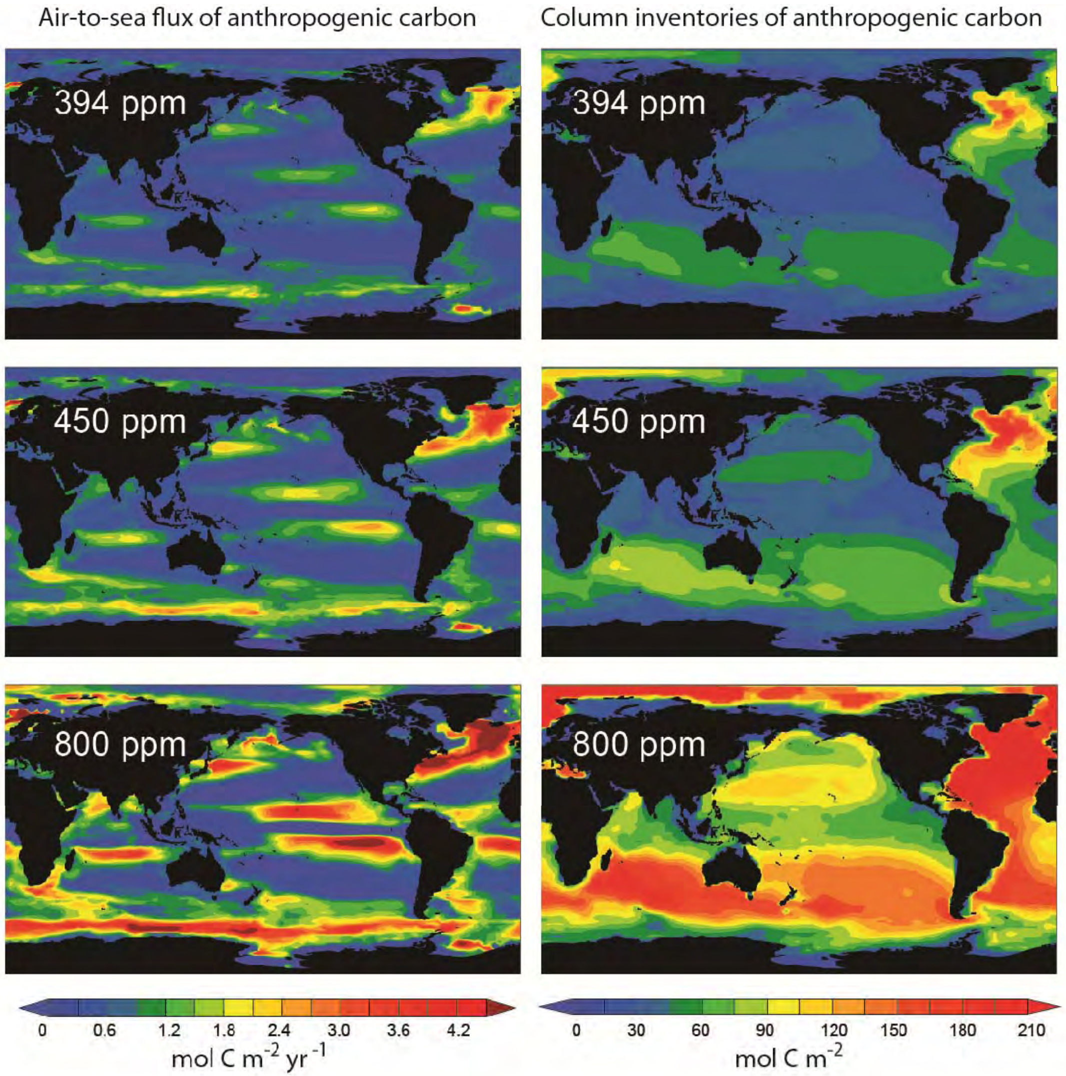


Figure 6

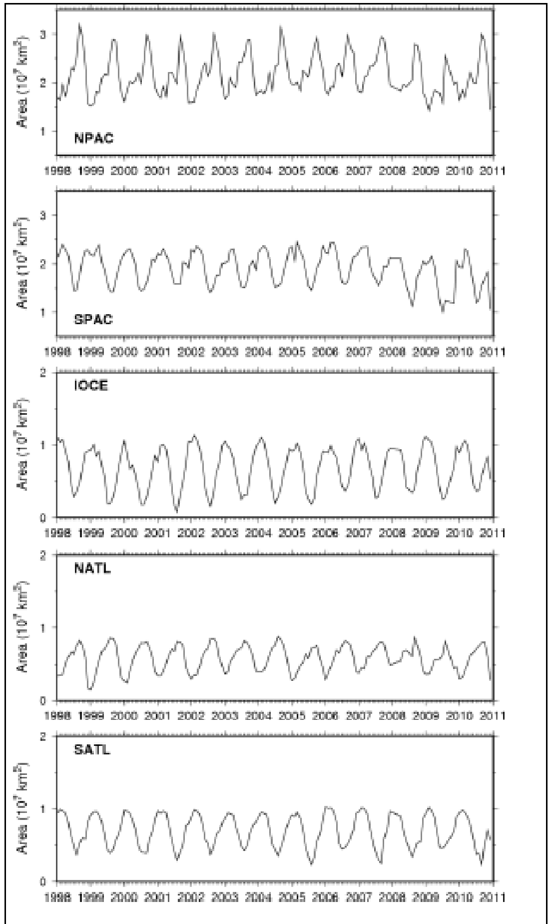


Fig. 2. Monthly time series of the size of the oligotrophic (Chl-a < 0.07 mg m^{-3}) region for each of the subtropical gyres shown in Fig. 1.

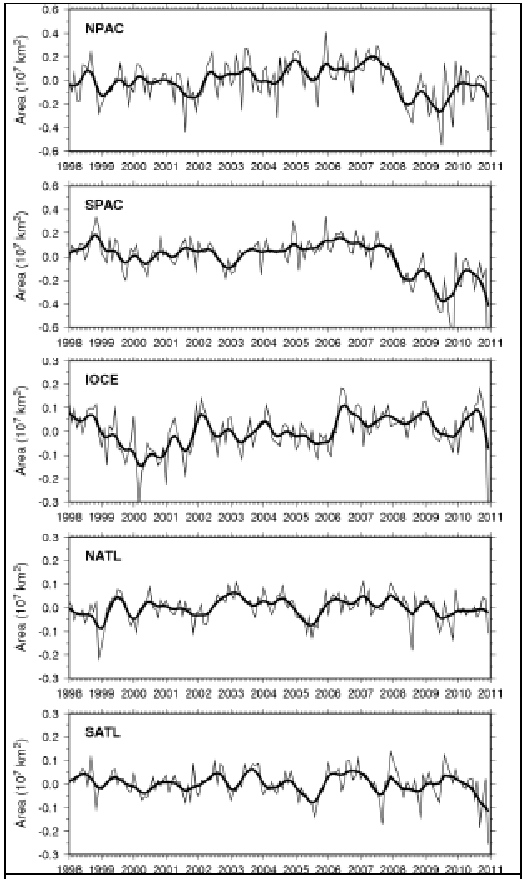


Fig. 3. Time series showing the interannual variability of the oligotrophic regions with the seasonal cycle removed (thin lines). The thick black lines are low-pass Filtered with a Gaussian filter using a one-year band-width.

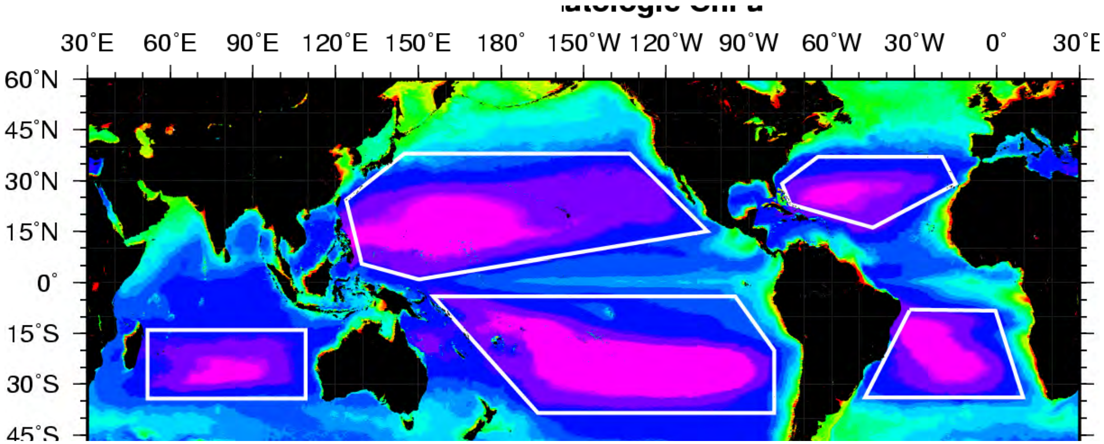
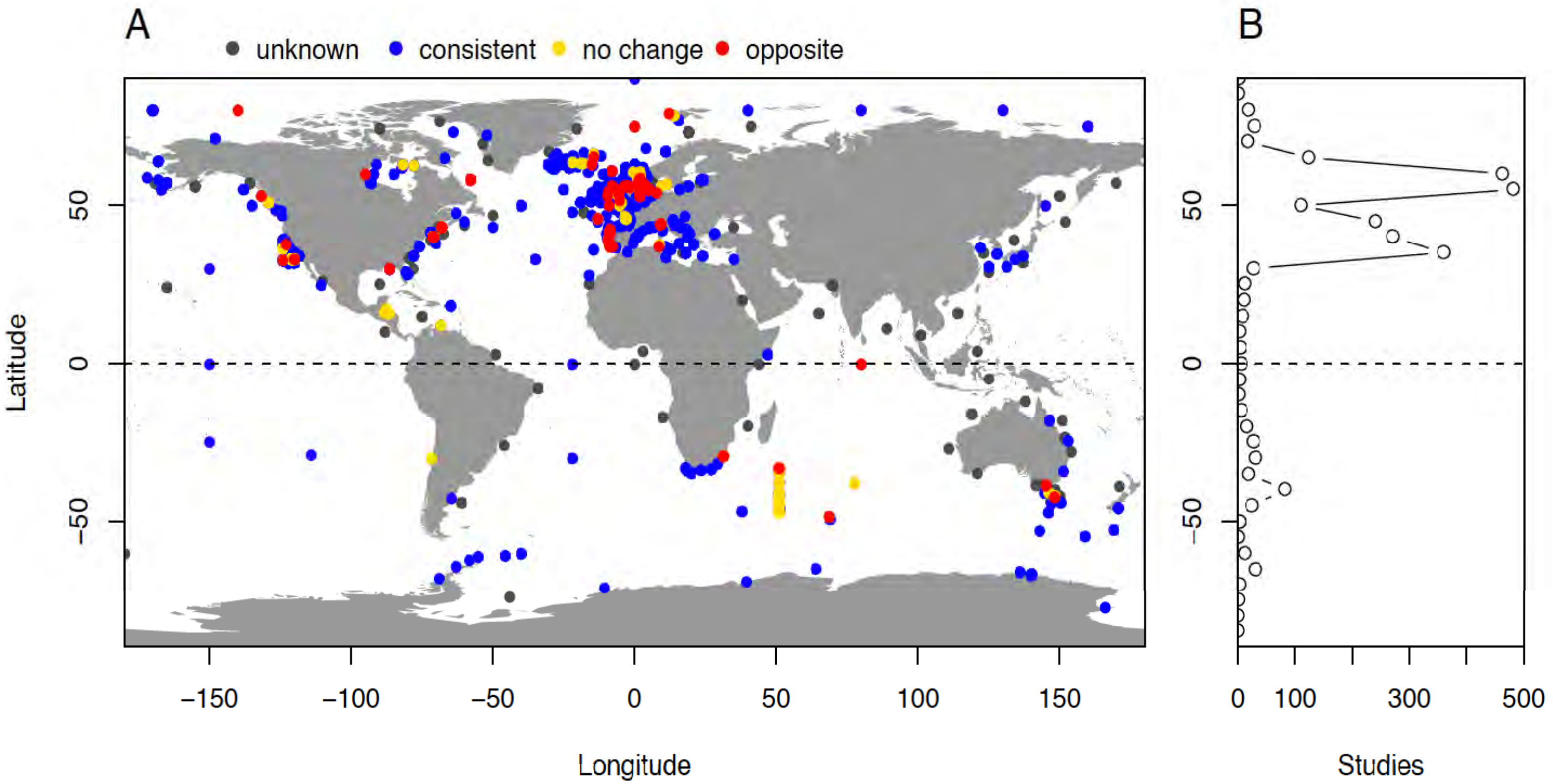


Figure 7



Global	Pacific	Indian	Atlantic	Semi-enclosed
2006	533	18	1134	174
74.4%	70.2%	61.1%	72.8%	93.0%

Figure 8

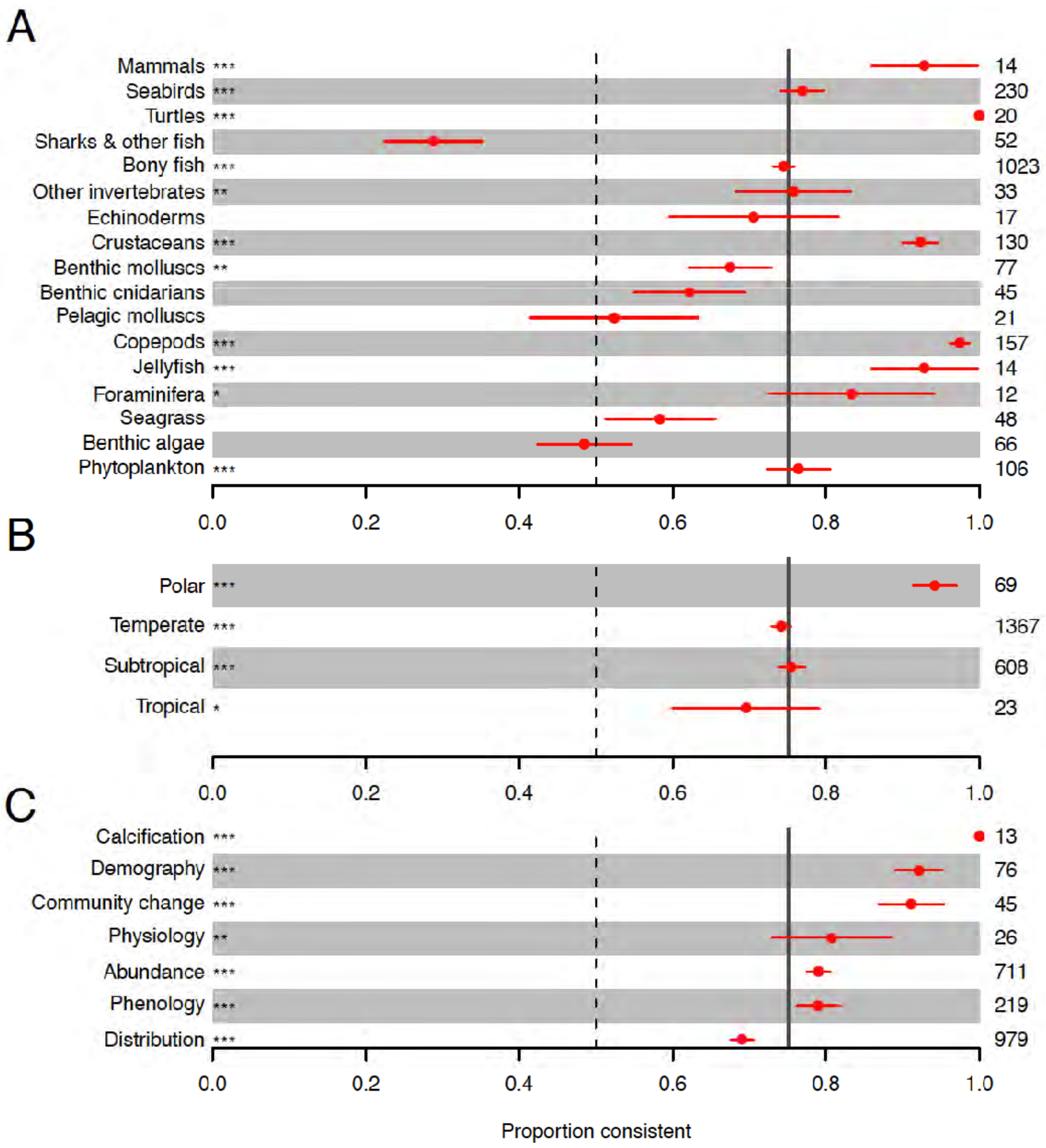

A
Mammals ***
Seabirds ***
Turtles ***
Sharks & other fish
Bony fish ***
Other invertebrates **
Echinoderms
Crustaceans ***
Benthic molluscs **
Benthic cnidarians
Pelagic molluscs
Copepods ***
Jellyfish ***
Foraminifera *
Seagrass
Benthic algae
Phytoplankton ***
14
230
20
52
1023
33
17
130
77
45
21
157
14
12
48
66
106
0.0
0.2
0.4
0.6
0.8
1.0
B
Polar ***
Temperate ***
Subtropical ***
Tropical *
69
1367
608
23
0.0
0.2
0.4
0.6
0.8
1.0
C
Calcification ***
Demography ***
Community change ***
Physiology **
Abundance ***
Phenology ***
Distribution ***
13
76
45
26
711
219
979
0.0
0.2
0.4
0.6
0.8
1.0
Proportion consistent

Figure 9

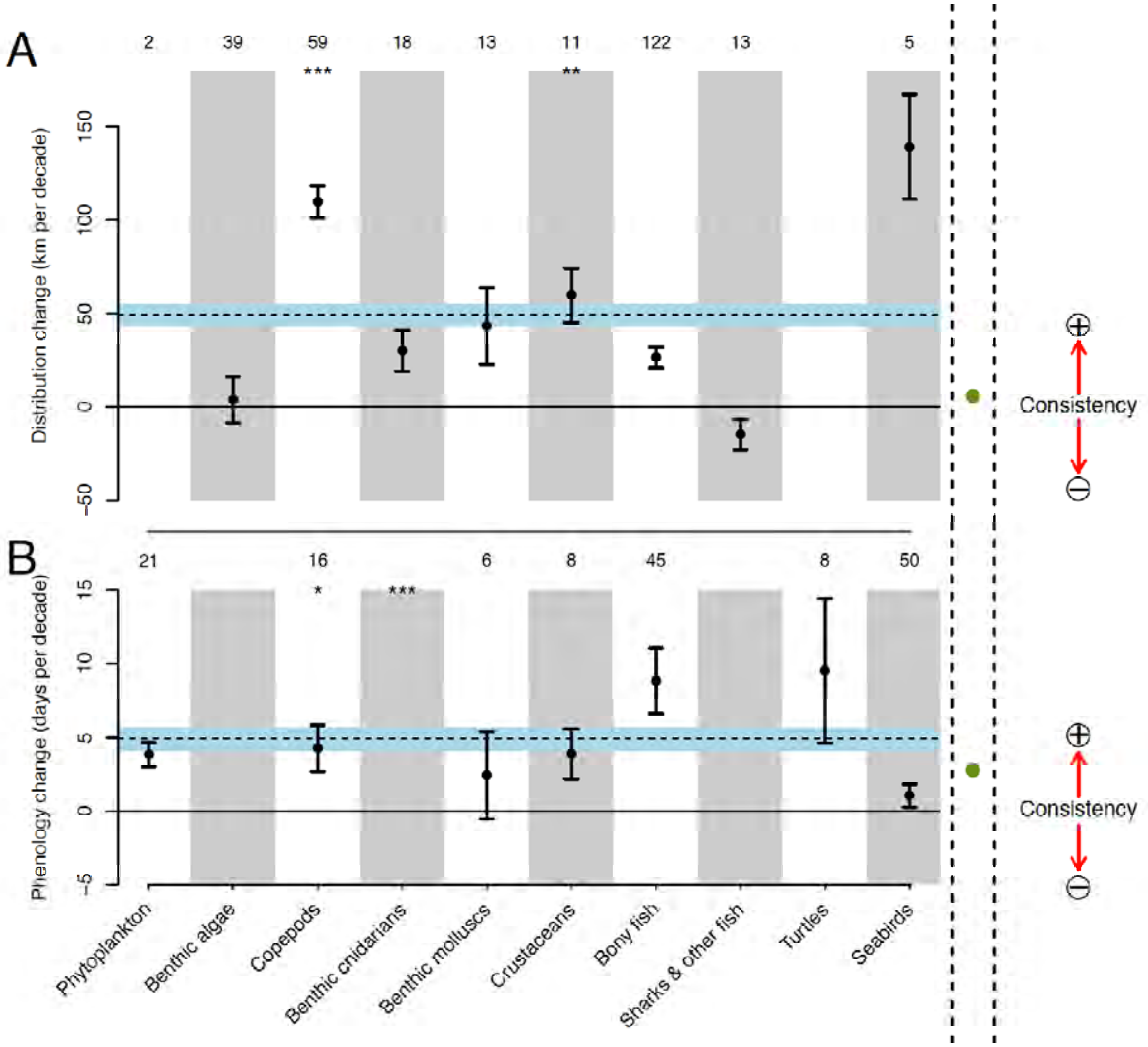

A
2
39
59
18
13
11
122
13
5
***
**
Distribution change (km per decade)
150
100
50
0
-50
⊕
Consistency
⊖
B
21
16
6
8
45
8
50
*
***
Phenology change (days per decade)
15
10
5
0
-5
⊕
Consistency
⊖
Phytoplankton
Benthic algae
Copepods
Benthic cnidarians
Benthic molluscs
Crustaceans
Bony fish
Sharks & other fish
Turtles
Seabirds

Figure 10

Figure 10. Regional oceans and seas. Left: Indian Ocean, middle: Atlantic Ocean and right: Pacific Ocean. Semi-enclosed mediterranean seas 1: Red Sea, 2: Persian Gulf, 3: American meditteranean sea (Gulf of Mexico and Caribbean Sea) 4: Baltic Sea, 5: (European) Mediterranean Sea 6: Australasian mediterranean sea.*T*

hese images are from Wikipedia, I've drop shapes over the semi-enclosed seas.

Figure 11

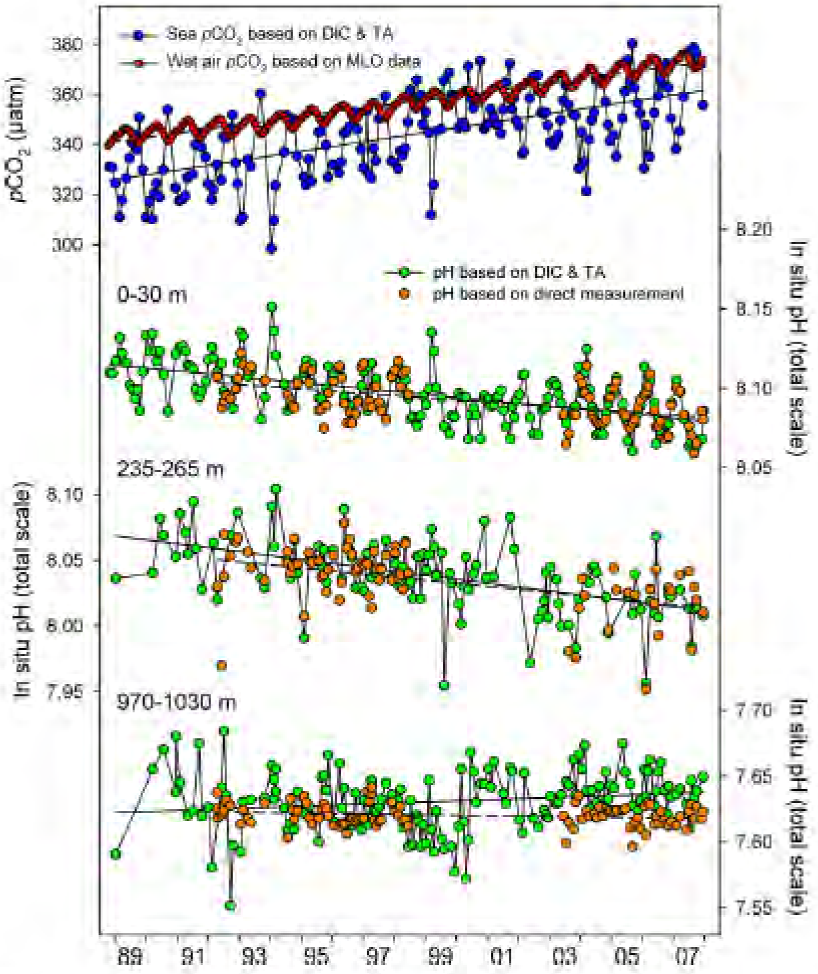


Fig. 1. Time-series of mean carbonic acid system measurements within selected depth layers at Station ALOHA, 1988–2007. (First image) Partial pressure of CO_2 in seawater calculated from DIC and TA (blue symbols) and in water-saturated air at in situ seawater temperature (red symbols). Linear regressions of the sea and air pCO$_2$ values are represented by solid and dashed lines, respectively. (Second, third, and fourth images) In situ pH, based on direct measurements (orange symbols) or as calculated from DIC and TA (green symbols), in the surface layer and within layers centered at 250 and 1000 m. Linear regressions of the calculated and measured pH values are represented by solid and dashed lines, respectively.

Dore et al 2009 PNAS

Figure 12 A

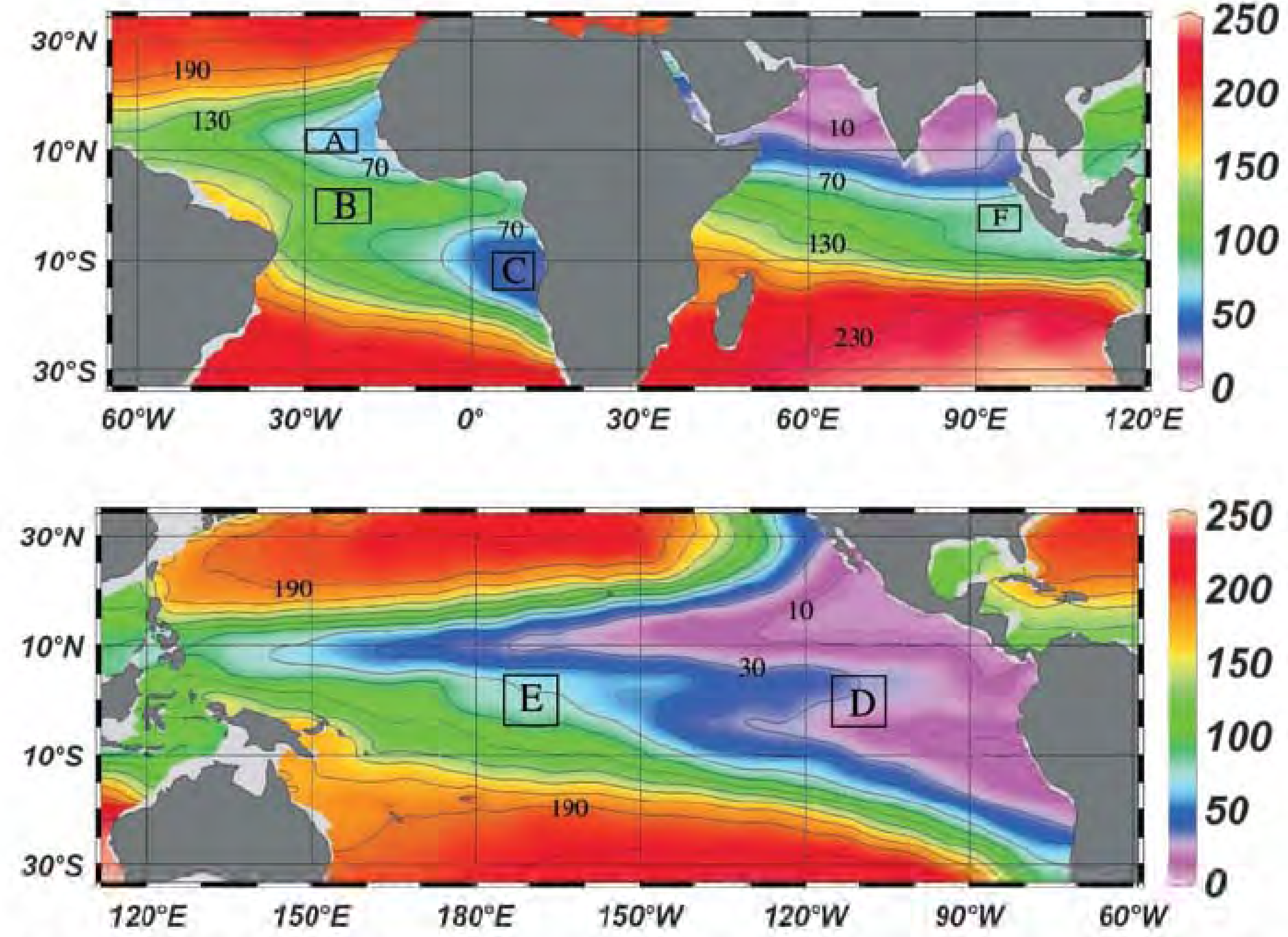


Fig. 1. Climatological mean (*18*) dissolved oxygen concentrations (µmol kg^{-1} shown in color) at 400 m depth contoured at 20-µmol-kg^{-1} intervals from 10 to 230 µmol kg^{-1} (black lines) using Ocean Data View (*19*) software. Analyzed areas (A to F, Table 1, and Fig. 2) are enclosed by black boxes.

Stramma et al. 2008

Figure 12 B

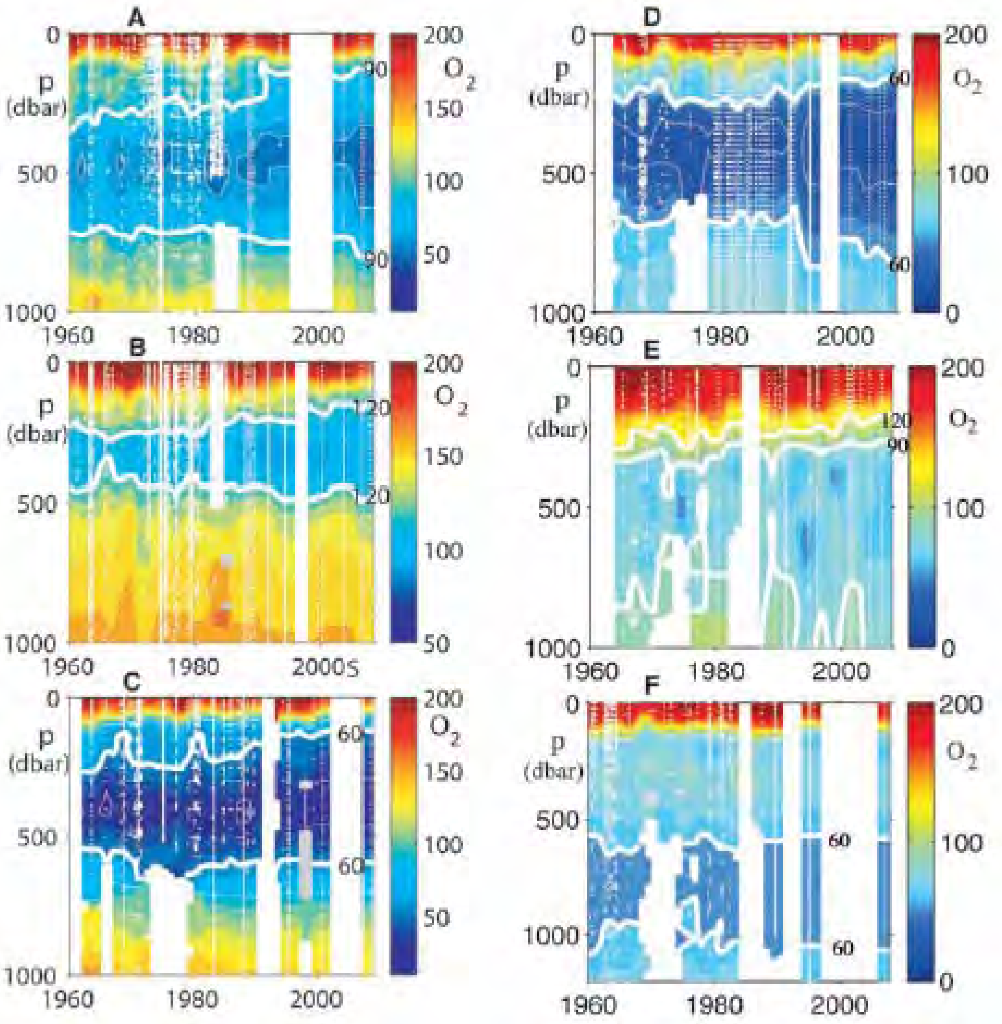


Fig. 2. Dissolved oxygen concentration (μmol kg^{-1} shown in color) maps (*20, 21*) versus time (1960–2008) and pressure (1 dbar ~ 1 m) with sample locations (white dots). (**A**) The eastern tropical North Atlantic (10° to 14°N, 20° to 30°W), contoured at 90 μmol kg^{-1} (thick white line). (**B**) The central equatorial Atlantic (3°S to 3°N, 28° to 18°W), contoured at 120 μmol kg^{-1} (thick white line). (**C**) The eastern tropical South Atlantic at (14° to 8°S, 4° to 12°E), contoured at 60 μmol kg^{-1} (thick white line). (**D**) The eastern equatorial Pacific Ocean (5°S to 5°N, 105° to 115°W), contoured at 60 μmol kg^{-1} (thick white line). (**E**) The central equatorial Pacific Ocean (5°S to 5°N 165° to 175°W), contoured at 90 and 120 μmol kg^{-1} (thick white lines). (**F**) The eastern equatorial Indian Ocean (5°S to 0, 90° to 98°E), contoured at 60 μmol kg^{-1} (thick white line).

Figure 13

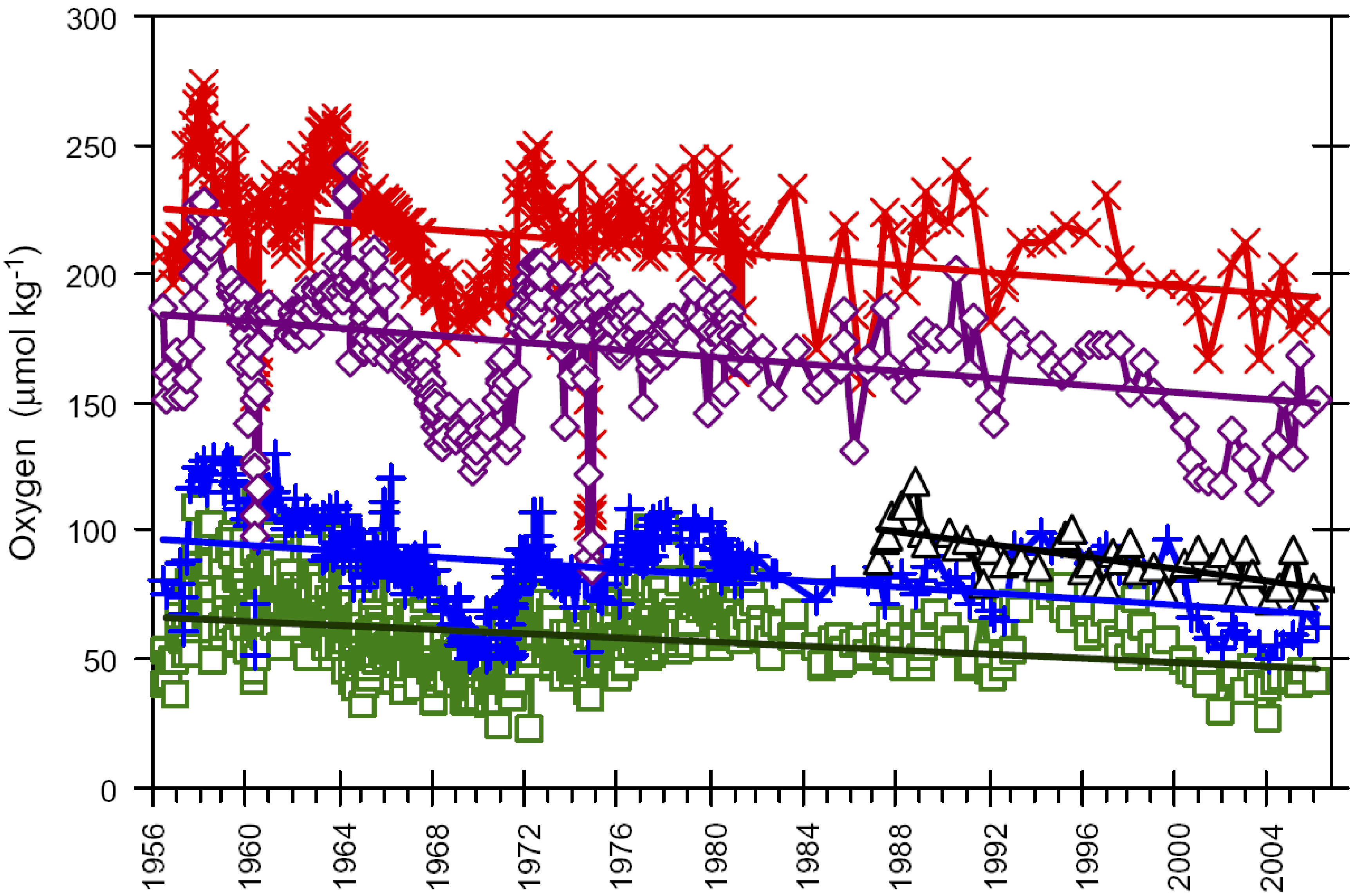

300
250
200
150
100
50
0
Oxygen (µmol kg^{-1})
1956
1960
1964
1968
1972
1976
1980
1984
1988
1992
1996
2000
2004

Figure 14

A

Warming trend OR velocity trends in SST for SW Pacific overlaid with obs from Fig 2 using unique symbols for taxa gps

B

Warming trend OR velocity trends in SST for Cal Current overlaid with obs from Fig 2 using unique symbols for taxa gps

C

Pacific	Bony fish	Seabirds	Sharks and rays	Pelagic molluscs	Benthic molluscs	Benthic cnidarians *	Forams	Copepods	Benthic crustacea
Whole	66 (295)	93 (101)	35 (20)	27 (11)	62 (21)	66 (32)	80 (10)	100 (6)	89 (9)
Northern	71 (208)	95 (93)	ND	27 (11)	71 (14)	54 (24)	80 (10)	100 (6)	89 (9)
Southern	55 (87)	75 (8)	35 (20)	ND	43 (7)	100 (8)	ND	ND	ND

Figure 14: a and b observations for Pacific Ocean. C Proportion of observations (%) consistent with climate change by taxa. Number of observations given in brackets. ND = no data. Only taxa groups with >5 observations shown. *anemones and corals

Figure 15

A

Warming trend OR velocity trends in SST for Med overlaid with obs from Fig 2 using unique symbols for taxa gps

B

Warming trend OR velocity trends in SST for Caribbean overlaid with obs from Fig 2 using unique symbols for taxa gps

C

Semi-enclosed Sea	Bony fish	Dinoflagellates	Crustacea*	Seagrass	Turtles	Benthic cnidarians
Mediterranean	100 (108)	57 (14)	100 (18)	100 (6)	100 (9)	ND
Caribbean and Gulf of Mexico	83 (18)	ND	ND	ND	ND	50 (8)

Figure 15: a and b observations for Mediterranean and Caribbean. C Proportion of observations (%) consistent with climate change by taxa. Number of observations given in brackets. ND = no data. Only taxa groups with >5 observations shown.

*mysids and crabs

Figure 16 (place marker)

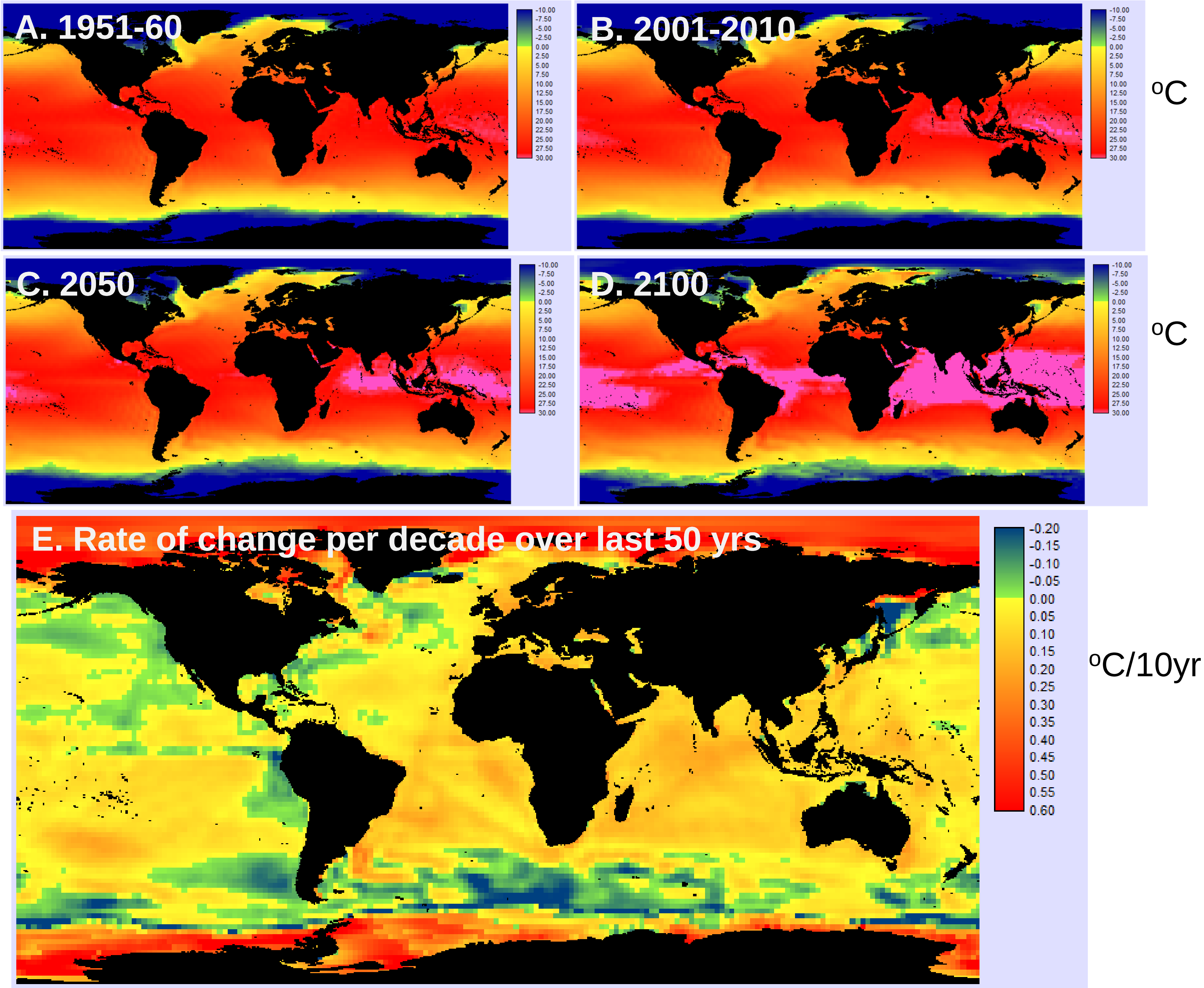


Figure 17

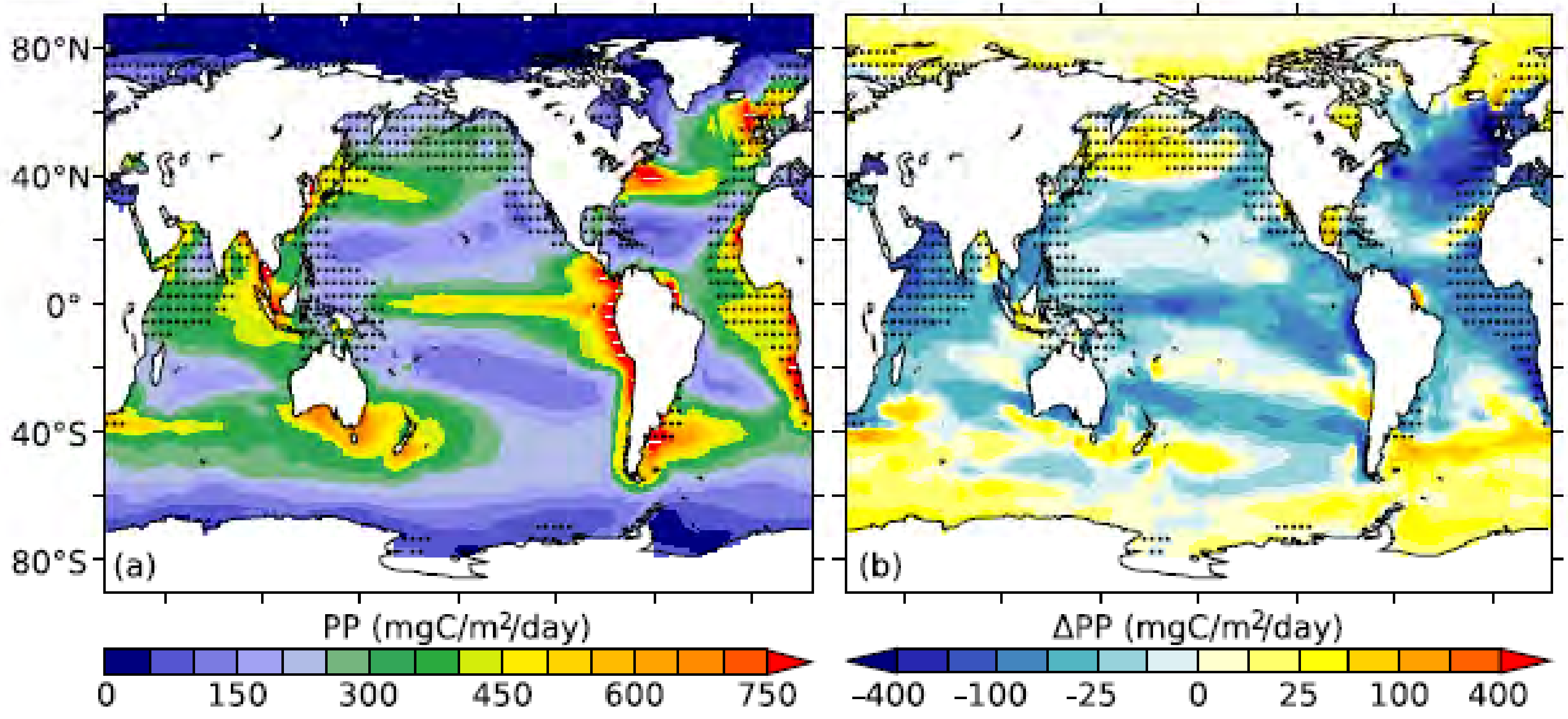


Figure 17. From [*Steinacher et al.*, 2010]. Left panel: Modeled mean primary production of four global models under preindustrial conditions (1860-1869). Right panel: Rate of change from preindustrial time to the end of 21st century (2090-2099).

Figure 18

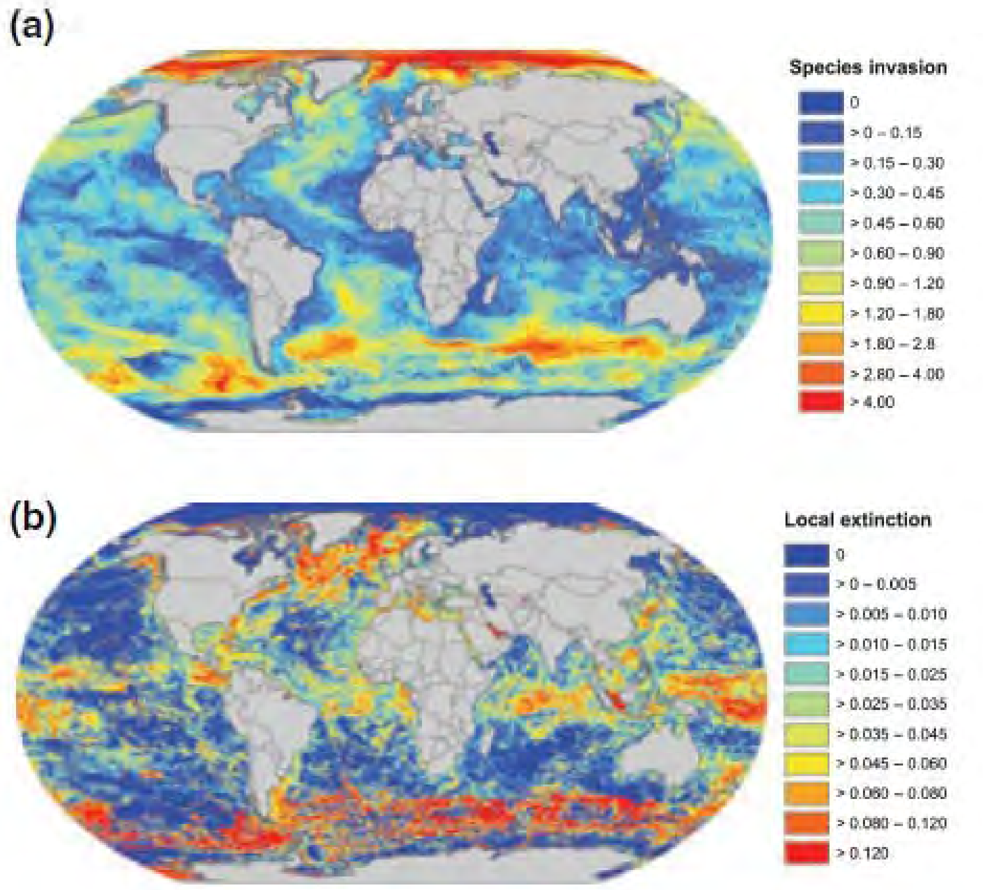


Figure 18. After Cheung et al. (2009). Projected distributional changes in fish species in 2050 relative to 2001-2005.