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OCEANS AND MARINE RESOURCES IN A CHANGING CLIMATE*

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The United States is an ocean nation—our past, present, and future are inextricably connected to and dependent on oceans and marine resources. Marine ecosystems provide many important services, including jobs, food, transportation routes, recreational opportunities, health benefits, climate regulation, and cultural heritage that affect people, communities, and economies across the United States and internationally every day. There is a wealth of information documenting

the strong linkages between the planet's climate and ocean systems, as well as how changes in the climate system can produce changes in the physical, chemical, and biological characteristics of ocean ecosystems on a variety of spatial and temporal scales. There is relatively little information on how these climate-driven changes in ocean ecosystems may have an impact on ocean services and uses, although it is predicted that ocean-dependent users, communities, and economies will likely become increasingly vulnerable in a changing climate. Based on our current understanding and future projections of the planet's ocean systems, it is likely that marine ecosystems will continue to be affected by anthropogenic-driven climate change into the future. This review describes how these impacts are set in motion through a suite of changes in ocean physical, chemical, and biological components and processes in US waters and the significant implications of these changes for ocean users and the communities and economies that depend on healthy oceans. US international partnerships, management challenges, opportunities, and knowledge gaps are also discussed. Effectively preparing for and responding to climate-driven changes in the ocean will require both limiting future change through reductions of greenhouse gases and adapting to the changes that we can no longer avoid.

Introduction

Marine ecosystems under US sovereignty, including areas under state and federal jurisdiction, generally extend from the shore to 203 nautical miles seawards. The area under federal jurisdiction spans 3.4 million square nautical miles of ocean—an area referred to as the US Exclusive Economic Zone (EEZ). The United States has the largest EEZ in the world, an area 1.7 times the land area of the continental United States and encompassing 11 different large marine ecosystems (LMEs). In 2004, the ocean-dependent economy generated $138 billion, or 1.2% of US gross domestic product (GDP) (Kildow et al. 2009). US ocean areas are also inherently connected with the nation's vital coastal counties, which make up only 18% of the US land area but are home to 36% of the US population and account for over 40% of the national economic output (Kildow et al. 2009).

These valuable marine ecosystems and the services they provide are increasingly at risk from a variety of pressures, including climate change and the related issue of ocean acidification (Osgood 2008, Doney et al. 2012). These pressures are affecting ocean physical, chemical, and biological systems, as well as human uses of these systems. Increasing levels of atmospheric carbon dioxide (CO_2) are one of the most serious problems because the effects are globally pervasive and irreversible on ecological timescales (National Research Council [NRC] 2011). The present CO_2 concentration is the highest on record in at least the last 800,000 years (based on ice core data) (Lüthi et al. 2008).

The two primary direct consequences of increased atmospheric CO_2 in marine ecosystems are increased ocean temperatures (Bindoff et al. 2007) and higher acidity (Doney et al. 2009). Increased acidity of the ocean is directly related to oceanic absorption of CO_2 from the atmosphere. The CO_2 reacts with seawater to change the chemical environment of the oceans fundamentally (Feely et al. 2010). However, oceanic absorption of CO_2 is dependent on water temperature and pH, and these mechanisms are likely to become less efficient as waters warm and pH decreases under future climate scenarios. Increasing temperatures produce a variety of ocean changes, including rising sea level, increased ocean stratification, decreased extent of sea ice, and altered patterns of ocean circulation, storms, precipitation, and freshwater input (Doney et al. 2012). In addition, non-climatic stressors resulting from a variety of human activities, including pollution, fishing impacts, and overuse, can interact with and exacerbate impacts of climate change. These impacts are expected to increase in the future with continued changes in the global climate system and increases in human population levels. These and other changes in ocean physical and chemical conditions (such as changes in oxygen concentrations and nutrient availability) are having an impact on a variety of ocean biological features (e.g., primary production, phenology, species distribution, species interactions and community composition), which in turn can have an impact on vital ocean services across the nation (Figure 1).

Projections of future change indicate that it is likely that marine ecosystems under US jurisdiction, and US activities and partnerships internationally, will continue to be affected by anthropogenic-driven climate change, and that those impacts will likely vary by magnitude and by region. Uncertainty regarding the rate and magnitude of climate-related changes in biophysical aspects of marine resources limits our current ability to assess socioeconomic impacts. However, the evidence that many climate-related changes are already occurring lends urgency to the need to prepare for additional change in the future.

Climate-driven physical and chemical changes in marine ecosystems

Covering more than two-thirds of Earth's surface, the oceans are a central component of the global climate system. The oceans help control the timing and regional distribution of Earth's response to climate change, primarily through their absorption of CO_2 and heat, resulting in observed changes to the physical and chemical properties of the oceans (Figure 2). The International Panel on Climate Change (IPCC) assessment released in 2007 projected that due to the persistence of greenhouse gases in the atmosphere, it is highly likely that the oceans will continue to warm, and these impacts will continue to be felt for centuries (IPCC 2007). Expected physical and chemical consequences for the oceans include increased sea-surface temperature, accelerated melting of Arctic ice, increased ocean acidity, sea-level rise, increased stratification of the water column, and changes in ocean circulation, climate patterns, and salinity.

Research shows that between 1961 and 2003, the average temperature of the upper 700 m of water increased by 0.2°C (Bindoff et al. 2007), arctic sea ice volume has shrunk by 75% over the last decade (Laxton et al. 2013), incidences of hypoxia (a condition by which an aquatic environment has oxygen concentrations that are insufficient to sustain most animal life) within US estuaries increased 30-fold since 1960 (Diaz & Rosenberg 2008), and ocean acidity increased by 30% over the past century (Feely et al. 2004). Warming of ocean waters increases the available energy used to create short-lived storms, and while the frequency of hurricanes and typhoons may not change, it is likely that a warming ocean will result in increased storm intensity (Knutson et al. 2010). As the ocean surface warms, stratification increases, resulting in warmer water remaining at the surface instead of mixing with cooler water below. Warm water is not as efficient at absorbing CO_2, and while this might have a slowing effect on ocean acidification, consequences include potential reductions in uptake of atmospheric CO_2 by the oceans. While there is some variability in salinity levels globally, recent analyses of water density and atmospheric data collected from 1970 to 2005 suggest that there are overriding changes, including acceleration, in the global hydrological cycle (Helm et al. 2010).

The physical and chemical changes taking place in the global oceans set the stage for subsequent effects on marine organisms, US communities and economies dependent on marine services, US governance and interactions with neighbouring countries, and potential adaptation strategies. A great deal of uncertainty remains with respect to how rapidly the physical and chemical attributes of the oceans will change in the future, as well as the magnitude of specific impacts and what, if any, potential feedbacks will occur. Key to advancing knowledge and projections of change will be sustained, long-term monitoring of the physical and chemical components of the world's oceans. Research and modelling are also needed to improve understanding and projection of oceanic properties at various temporal and spatial scales. While historical data can provide important insight into patterns, trends, and trajectories of change, additional information collected over the coming years will be vital for predicting future responses to climate change.

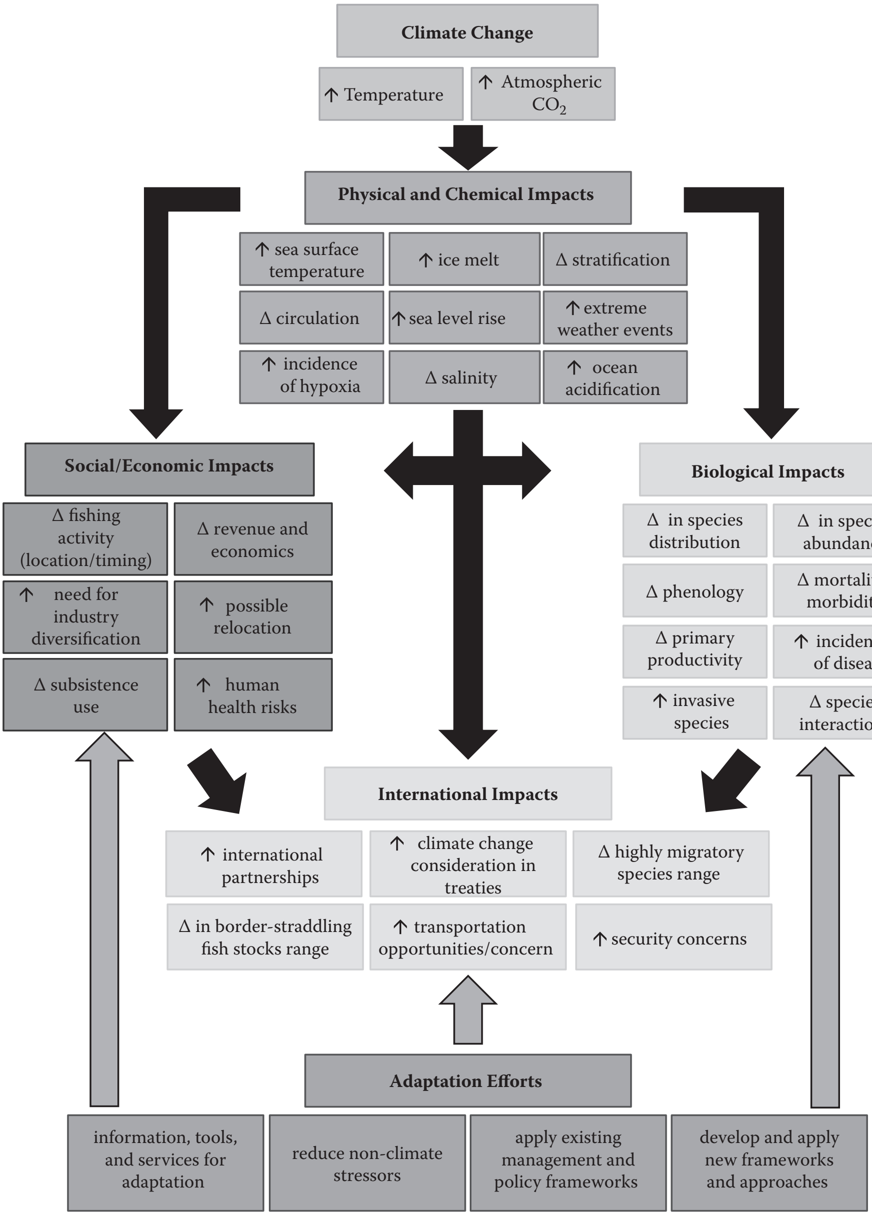


Figure 1 (See also colour figure in the insert) Impacts of climate change on marine ecosystems. Conceptualized diagram depicting how climate change impacts, such as increased temperature and ocean acidification, set in motion a suite of changes in the oceans' physical, chemical, and biological components and processes, resulting in significant implications for ocean users and the communities and economies that depend on healthy oceans. Changes in the physical and chemical makeup of the ocean is having an impact on marine organisms and ecosystems, local economies such as fishing and tourism, as well as becoming an ever-increasing topic of consideration in international conservation communities. Adaptation efforts are beginning to be put in place to try to counter climate change impacts as well as help build ecosystem and socioeconomic resiliency. Black arrows represent impacts driven by climate change either directly or indirectly. Gray arrows represent countering effects of various adaptation efforts. ↑ indicates where climate change is predicted to increase the incidence or magnitude of that attribute, and Δ indicates attributes where the impact of climate change on that attribute is variable.

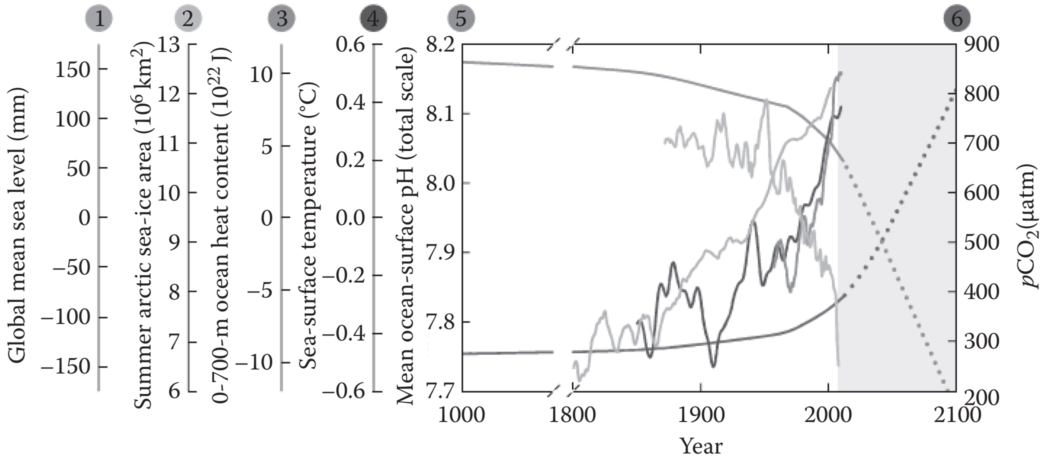


Figure 2 (See also colour figure in the insert) Observed changes to the physical and chemical properties of the oceans. Changes in (1) global mean sea level (teal line; Jevrejeva et al. 2008); (2) summer Arctic sea-ice areas (yellow line; Walsh & Chapman 2001); (3) 0- to 700-m ocean heat content (orange line; Levitus et al. 2009); (4) sea-surface temperature (brown line; Rayner et al. 2006); (5) mean ocean surface pH (blue line, National Research Council 2010); and (6) pCO_2 (red line; Petit et al. 1999). Light purple-shaded region denotes projected changes in pH and pCO_2 consistent with the IPCC's twenty-first-century A2 emissions scenario with rapid population growth. (Modified from Doney et al. 2012.)

Ocean temperature and heat trapping

According to the IPCC (2007), "most of the observed increase in globally averaged temperatures since the mid-twentieth century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations," and current modelling systems predict that it is highly likely that the rate of warming will accelerate over the next few decades. Air temperature and sea-surface temperature are strongly correlated, and just as increasing concentrations of atmospheric CO_2 and other greenhouse gases lead to increased air temperatures, ocean temperatures are also expected to increase. Indeed, estimates show that from 1955 to 2008, approximately 84% of the added atmospheric heat was absorbed by the oceans (Levitus et al. 2009). The oceans are now experiencing some of the highest temperatures on record (Bindoff et al. 2007).

Increases in sea-surface temperature are likely to accelerate over the next few decades, along with a predicted increase in global mean surface air temperature between 1.1°C (under low-CO_2 emission scenario B1; IPCC 2007) and 6.4°C (under high-CO_2 emission scenario A1FI; IPCC 2007) by the end of the twenty-first century (Meehl et al. 2007). Even now, historical data show that the global ocean surface temperatures for January 2010 were the second warmest on record since 1880 (when records began), and in 2009, sea-surface temperatures from June to August reached 0.58°C above the average global temperature for the twentieth century (Hoegh-Guldberg & Bruno 2010).

It is important to note that changes in ocean temperature are not uniform, and while the average temperature has increased globally, localized temperature decreases have also been observed. The differences in temperature observed locally are mostly due to the atmospheric and oceanic processes that govern both the gains and the losses in sea-surface temperatures (Deser et al. 2010). Dominant atmospheric factors driving ocean temperature include wind speed, air temperature, cloudiness, and humidity; dominant oceanic factors include heat transport by currents and vertical mixing (Figure 3) (Deser et al. 2010). Oceanic and atmospheric processes play off one another, and heat exchange between the oceanic and atmospheric environments is a driving force of atmospheric circulation.

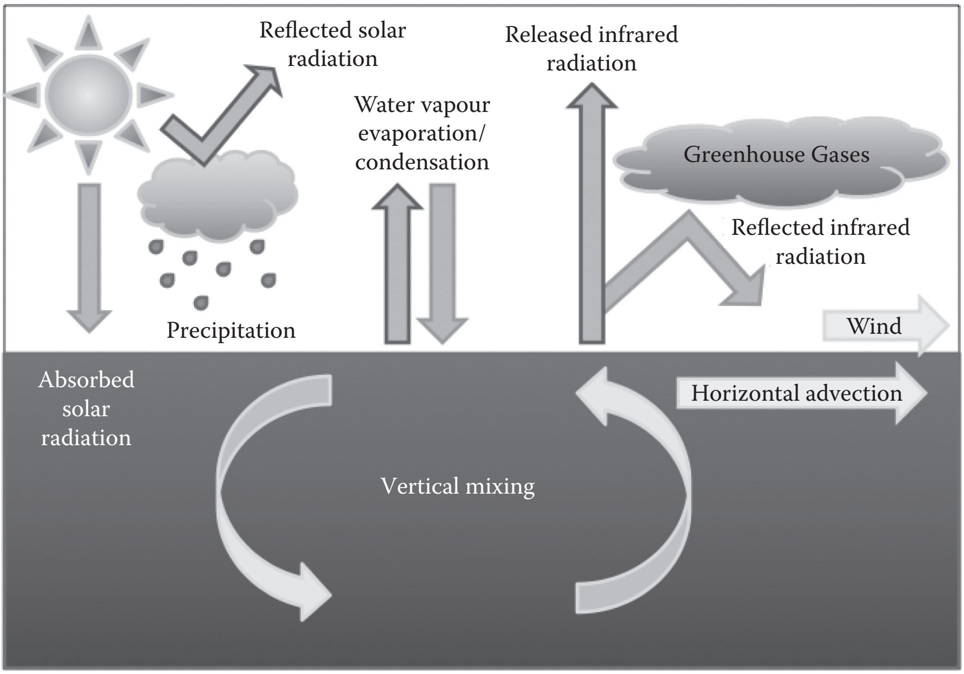


Figure 3 Exchange of heat between the ocean and the atmosphere. Idealized depiction of how solar energy is absorbed by the earth's surface, causing the earth to warm and to emit infrared radiation. The greenhouse gases then trap the infrared radiation, thus warming the atmosphere. Wind-induced turbulence, horizontal advection, and vertical mixing of the ocean waters aid in heat exchange by constantly mixing the surface layer of the ocean.

Evaporation rates are expected to increase as a result of climate change, leading to an increase in atmospheric water vapour. Water vapour is itself a potent greenhouse gas (much more so than carbon dioxide); atmospheric water vapour reflects heat emitted from Earth in the form of infrared radiation back down to the surface, which increases the amount of heat that is retained in the atmosphere (Randall et al. 2007). The potential exists for a cycle of increased water vapour stimulating increased warming and thus continued production of water vapour, leading to a 'runaway greenhouse effect' (Trenberth et al. 2009). In addition, water vapour stimulates cloud formations as it cools and condenses in the upper atmosphere, and clouds can cause both warming and cooling conditions. They warm by reflecting Earth's heat back down as mentioned, and they cool by reflecting solar radiation back into space (Stephens et al. 2008). It is uncertain which cloud effect, warming or cooling, will have the greatest impact, but the preponderance of evidence indicates that it will be an increase in warming (e.g., Dessler 2011), which is likely to cause upper ocean temperatures to increase at a faster rate than observed during the last few decades (Friedlingstein et al. 2001).

The interplay between oceanic and atmospheric heat exchanges has important implications for global weather and climate patterns. For example, sea-surface temperatures in the Pacific Ocean influence winter precipitation in the south-western United States (Wagner et al. 2010). Observations indicate that changes in sea-surface temperature in the tropical North Atlantic affect the precipitation in North and Central America, leading to increased incidence of drought throughout the United States and Mexico (Kushnir et al. 2010). Tropical storms form over warm ocean waters, which supply the energy for hurricanes and typhoons to grow and move (Trenberth et al. 2007). Conversely, the oceans have tremendous thermal inertia, which can slow and dampen the rate of climate change (Schewe et al. 2010). The significantly larger heat capacity of the deep ocean is particularly important when looking at timescales of decades to millennia, which are relevant for long-term climate change. Ocean currents and mixing by gyres, winds, and waves can transport and redistribute heat to deeper ocean layers. Heat energy can reside in this deep reservoir for centuries, further stabilizing Earth's climate and slowing the effects of climate change (Hansen et al. 2005).

Perhaps one of the most destructive effects of ocean warming comes in the form of sea-level rise. Most of the sea-level rise observed over the past several centuries can be accounted for by two major variables: the amount of water that is being released by landlocked glaciers and ice sheets and the thermal expansion or contraction of the oceans. Complete loss of arctic glaciers and small ice caps has the potential to raise future sea levels by about 0.2–0.7 m (IPCC 2007). Loss of Greenland and Antarctic ice sheets could increase that estimate by several metres; however, there is greater uncertainty surrounding those estimates. In the case of thermal expansion, given an equal mass, the total volume of ocean waters decreases when ocean temperatures drop and expands when temperatures increase. Thermal expansion was responsible for approximately 30% of the rise in sea level for the period 1961–2003 (Cazenave & Llovel 2010). Thermal expansion associated with increased temperature due to CO_2 emissions predicts an irreversible global average sea-level rise of at least 0.4–1.0 m if twenty-first century CO_2 concentrations exceed 600 parts per million by volume (ppmv) (current level is 385 ppmv) and as much as 1.9 m for a peak CO_2 concentration exceeding about 1000 ppmv (IPCC 2007), and these estimates are in addition to sea-level rise associated with ice melt described previously.

As global temperatures continue to increase, sea-level rise will become more extensive, with impacts on US coastal communities and ecosystems.

Loss of Arctic ice

As a result of warming temperatures, Arctic sea ice has been decreasing in extent throughout the second half of the twentieth century and the early twenty-first century (Figure 4A) (Maslanik et al. 2007, Nghiem et al. 2007, Comiso & Nishio 2008, Deser & Teng 2008, Alekseev et al. 2009, Arctic Marine Shipping Assessment [AMSA] 2009). Arctic sea ice naturally extends surface coverage each winter and recedes each summer, but the rate of overall loss since 1978, when satellite records began, has accelerated (IPCC 2007). The summer of 2007 saw a record low, when sea ice extent shrank to approximately 3 million km^2, approximately 1 million km^2 less than the previous minima of 2005 and 2006. Every year since then, September ice extent has been lower than in years prior to 2007, with 2011 extent being second lowest compared with 2007 (Perovich et al. 2011, Stroeve et al. 2011). Overall, the observed sea ice extent for the years 1979 to 2006 indicates an annual loss of approximately 3.7% per decade (Comiso et al. 2008) and an overall 42% decrease in thick, multi-year ice over a similar time period (Figure 4B) (Giles et al. 2008, Kwok & Untersteiner 2011). Over the last decade, arctic sea ice volume has shrunk by 75% (Laxton et al. 2013). The relative impacts of the loss of thicker, older ice versus the younger, thinner ice are currently not well understood.

In recent decades, the magnitude of warming in Arctic near-surface air temperatures has been approximately twice as large as the global average, a phenomenon known as 'Arctic amplification' (Serreze & Francis 2006, G. Miller et al. 2010), an effect largely due to diminishing sea ice (Screen & Simmonds 2010). Sea ice is efficient at reflecting solar energy; the much darker ocean surface is more effective at absorbing solar energy. Therefore, as reflective sea ice is lost, further warming of the ocean occurs, leading to additional ice melt (Serreze & Barry 2011). Decreases in snow and ice cover may ultimately decrease global albedo (the reflection of solar radiation), therefore amplifying warming, particularly at high latitudes (Bony et al. 2006, Soden & Held 2006, Randall et al. 2007). The roles of reductions in snow and changes in atmospheric and oceanic circulation, cloud cover and water vapour in Arctic amplification are still uncertain. Nevertheless, evidence suggests that strong positive ice-temperature feedbacks have emerged in the Arctic, increasing the chances of further rapid warming and sea-ice loss.

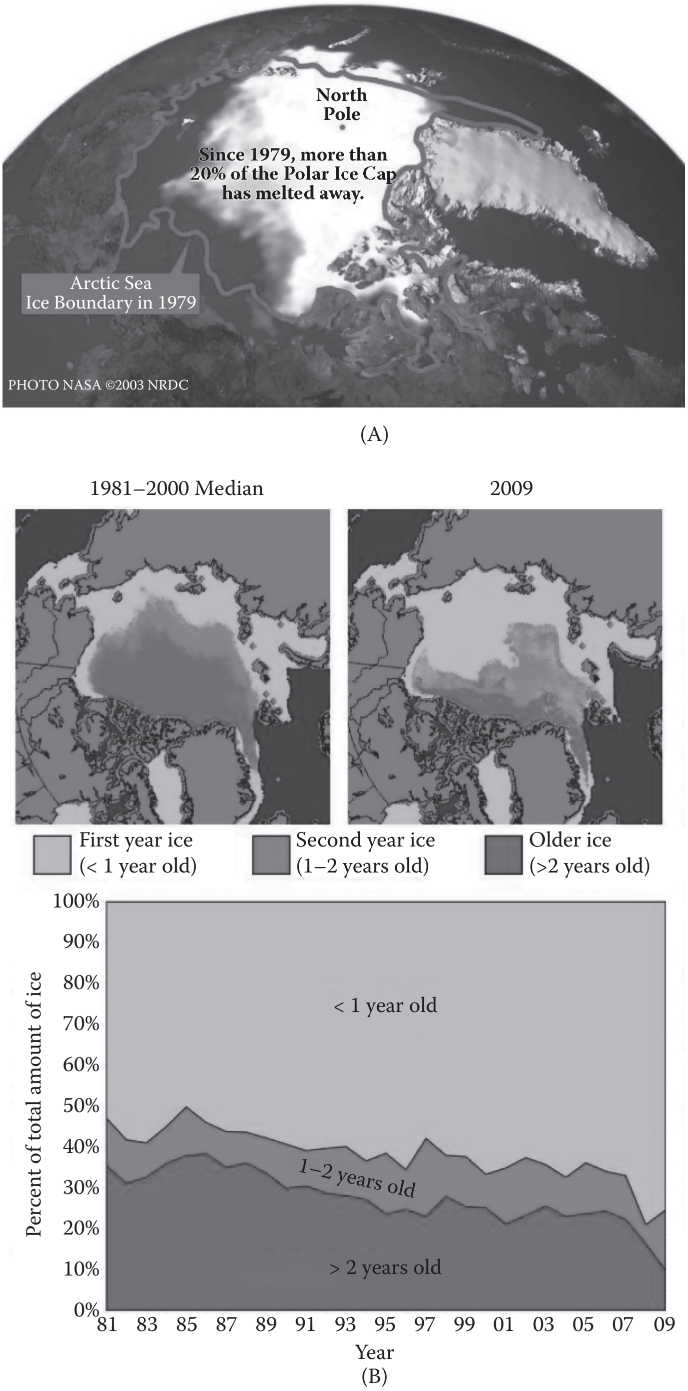


Figure 4 (See also colour figure in the insert) Changes in Arctic sea-ice extent and thickness. (A) Change in Arctic sea-ice boundaries from 1979 to 2007. (Photo NASA © NRDC.) (B) At top left, median image of sea-ice thickness at the end of each February cycle for the 1981–2000 time frame. On top right, the sea ice thickness for 2009. Bottom, percentage of ice that is new (<1 year old), 1–2 years old, and more than 2 years old per year from 1981 to 2009. (From the National Snow and Ice Data Center, courtesy J. Maslanik and C. Fowler, University of Colorado.)

These changes have consequences for polar ecosystems as well as human communities and activities. Decreasing Arctic sea ice also affects continental shelves downstream of the Arctic. The north-eastern US continental shelf has experienced a freshening over the past 30 years as a result of the advective supply of fresh water from the Arctic or Labrador Seas (Greene et al. 2008). Perhaps the most devastating consequence of melting polar ice will also be on sea-level rise, as noted in the preceding section.

The Arctic is likely moving toward a new state as more and more old ice is removed through increased melt rates and new ice becomes the dominant feature. The IPCC (2007) projections suggest that the Arctic may be virtually ice free in the summer by the late twenty-first century. However, others predict that reductions may happen even more rapidly, as previous projections utilized coupled air-sea-ice climate models that tend to overestimate ice thickness, and hence an ice-free Arctic in summer could occur as early as 2030 (Stroeve et al. 2008).

Salinity

Salinity refers to the salt content of the oceans. Contributors to salinity include precipitation and freshwater input (resulting in decreased salinity) and evaporation and terrestrial mineral deposits (resulting in increased salinity). Ocean salinity changes are an indirect but potentially sensitive indicator for detecting changes in precipitation, evaporation, river run-off, and ice melt. Thus, salinity may function as a proxy for identifying climate-driven changes in Earth's hydrological cycle (Helm et al. 2010).

The globally averaged surface salinity change to date is small, whereas basin averages are more noteworthy: increased salinity for the Atlantic, freshening in the Pacific, and a near-neutral result for the Indian Ocean (Durack & Wijffels 2010). Cravatte et al. (2009) uncovered large changes to ocean properties in the tropical western Pacific, indicating that a freshening and density decrease had occurred in the 1955–2003 period. Despite overall increased salinity in the Atlantic, studies conducted in the Scotian Shelf and Gulf of Maine waters showed a decrease in salinity (Greene et al. 2008). One of the main reasons for this is the melting of Arctic sea ice and resulting freshwater input into the Labrador Current. Another influence on decreased salinity in the Gulf of Maine is increased precipitation. Many climate models predict that there will be an increase in all forms of precipitation for the Gulf of Maine area (Wake et al. 2006), increasing river flow and terrestrial run-off. This input of fresh water will be especially large in the spring, when there is typically high river flow as pack ice melts and travels through the watershed (Wake et al. 2006). These inputs of fresh surface water inhibit the vertical mixing of the upper portion of the water column within the Gulf of Maine, and the resulting increased stratification prevents nutrients from being brought into the surface layer. Reductions in available nutrients affect phytoplankton productivity, the base of the food web, and these effects can cascade up to larger organisms like fish and marine mammals.

Changes to the global hydrological cycle are anticipated as a consequence of anthropogenic climate change (Held & Soden 2006, IPCC 2007). Even a small variation in the hydrological cycle, and resulting impacts on ocean salinity, can have a dramatic effect on the marine environment (Holland et al. 2001). Changes in salinity affect density parameters, as salt water is denser than fresh water, which in turn affects stratification. Ocean circulation, driven by temperature and salinity, may also be impacted. As cold, high-salinity water sinks at the poles, warmer, lower-salinity water is pulled from the equator to replace it (Broecker 1991), and if salinity declines due to climate-related increases in precipitation and glacial melt, it is possible that ocean circulation will begin to slow (Bindoff et al. 2007). Slowing of the oceans' circulation may result in dramatic changes to Earth's climate.

Stratification

Stratification, or layering, of ocean water is a naturally occurring phenomenon that is important to water column structure, circulation, and marine productivity. Water density is strongly influenced by temperature and salinity, with less-dense, warmer surface waters floating on top of denser, colder waters. Warming of the upper layers of the oceans enhances the density difference between the surface mixed layer and the deeper waters beneath. All else being equal, as waters warm, this increased density difference strengthens the vertical stratification of the oceans and suppresses vertical mixing across the density gradient. The result is contrasting effects on nutrient and light availability for phytoplankton growth. On the one hand, stratification reduces nutrient influx from deep, nutrient-rich waters into the surface mixed layer, thus limiting the availability of nutrients for phytoplankton growth (Behrenfeld et al. 2006, Huisman et al. 2006). On the other hand, stratification keeps phytoplankton in the surface mixed layer, resulting in improved light conditions (Huisman et al. 1999, Berger et al. 2007). Increased stratification and its effect on phytoplankton productivity can have negative consequences for coastal ecosystems. For example, warming of the surface waters in Southern California between 1951 and 1993 resulted in an 80% decrease in phytoplankton and zooplankton biomass, as well as decreased coastal upwelling and nutrient availability (Palacios et al. 2004).

Stratification varies regionally due to mixing, upwelling, and the uneven distribution of sea-surface temperatures. Many waters in the tropics and subtropics, such as those surrounding the Pacific Islands, are permanently stratified. Nutrient concentrations in the surface mixed layer of these waters are strongly depleted and are characterized by extremely low primary production. Climate-ocean models predict that, by the year 2050, due to ocean warming, the ocean area covered by permanent stratification will have expanded by 4.0% and 9.4% in the Northern and Southern Hemispheres, respectively (Sarmiento et al. 2004), thereby reducing overall ocean productivity (Behrenfeld et al. 2006). However, these predictions are surpassed by recent observations, which indicate a much faster expansion of the ocean's least-productive waters between 1998 and 2006 (Polovina et al. 2008).

In the temperate zone and at high latitudes, waters are not permanently stratified, and deep mixing during winter or spring provides nutrients into the surface layer. In these regions, phytoplankton growth is often light-limited in winter due to short day lengths as well as deep vertical mixing. Warming temperatures lead to earlier onset of stratification in spring, which retains phytoplankton in the well-lit surface layer, where they can take advantage of nutrients that have not yet been depleted, thereby favouring their growth. This leads to an earlier spring bloom and the potential for a substantially longer growing season in the temperate zone (Winder & Schindler 2004, Peeters et al. 2007).

Stratification can also be affected through changes in precipitation. Climate-induced precipitation increases will introduce fresh water into nearshore environments, either directly through rainfall or indirectly through increased run-off from the terrestrial environment. This freshening will tend to increase stratification, resulting in decreased diffusion of oxygen and nutrients. Decreasing oxygen concentrations will negatively affect biological communities and secondary production and disrupt biogeochemical cycles (Rabalais et al. 2009). Thus, climate-related changes in stratification are likely to cause subsequent impacts on inshore and nearshore US ecosystems.

Changes in precipitation and extreme weather events

Climate change influences winds and precipitation may be moderate but vary regionally (Trenberth 2011). Ironically, because of increased evaporation (as mentioned), some areas will experience intense surface drying (throughout the subtropics) such that there is an increased risk of flooding when intense storms occur (Trenberth 2011). In other areas, increased humidity may lead to more intense storms and hence more extreme precipitation and wind events. It is likely that warming temperatures will lead to some shifts in precipitation from snow to rain, resulting in decreased snowpack and earlier snow melts (Trenberth 2011). Taken together, climate change is likely to influence Earth's hydrological cycle and the character of weather events.

Winds

Winds can have a major influence on marine ecosystems. In fact, wind changes may be more important than temperature changes for inducing the stratification effects mentioned; however, wind predictions have higher uncertainty. Global wind stress has increased since 1999 and shows variable impacts regionally (Ecosystem Assessment Program [EAP] 2009). These changes in wind stress may be linked to climate regimes (such as the North Atlantic Oscillation [NAO], Pacific Decadal Oscillation [PDO], and the El Niño Southern Oscillation [ENSO]), as well as a northwards shift in the location of the jet stream (Archer & Caldeira 2008). If wind patterns or intensities change, currents and their effects on coastal waters might change, with potential consequences for oxygen concentrations. For example, off the Oregon and Washington coasts, wind-driven shifts in the California Current region occurred in 2002 and subsequent years, altering upwelling dynamics and resulting in extensive hypoxia along the inner continental shelf (Grantham et al. 2004, Chan et al. 2008). Climate-related changes to wind and ocean currents are also likely to interact with non-climatic stressors (e.g., the addition of excessive nutrients from terrestrial run-off), further increasing the incidence and severity of hypoxic (reduced oxygen) and anoxic (lack of oxygen) events.

Precipitation

Precipitation is an important part of Earth's climate system, linking the global water and energy cycles through condensational heating of the atmosphere and providing a link between the hydrological cycle and radiative processes, such as cloud feedback. Precipitation forms as water vapour is condensed, usually in rising air that expands and cools. Climate change impacts on the frequency of precipitation events will likely be moderate; however, precipitation events are predicted to become more intense (Trenberth et al. 2003). Changes in precipitation can adversely affect the supply of water for humans, agriculture, and ecosystems. Modelling predictions of future precipitation changes currently have high uncertainty over certain regions and particularly at small regional scales. However, advances in modelling show that a robust characteristic of anthropogenic climate change is the shifting of precipitation patterns and storm tracks (Held & Soden 2006, Seager et al. 2007). Also, as the climate warms, the percentage of precipitation that falls as snow is likely to decrease. Implications of decreased snowfall include earlier snowmelt, diminished snowpack, and thus a temporal change in stratification due to the timing of freshwater input into coastal and marine environments (Trenberth et al. 2003).

Storms

There is growing concern about the potential for climate-related impacts on storm events. The record-breaking hurricane season in the North Atlantic in 2005 had the largest number of named storms (28), the largest number of hurricanes (15), the most intense hurricane in the Gulf of Mexico (Rita), and the most damaging hurricane on record (Katrina), with Katrina the deadliest in the United States since 1928 (IPCC 2007). Uncertainty remains regarding the effects of climate change on storm intensity. Multidecadal variability and the lack of high-quality tropical cyclone records prior to routine satellite observations (which began in approximately 1970) complicate the detection of long-term trends in extreme weather events (Blunden et al. 2011). However, using downscaling based on the ensemble mean of 18 global climate change projections, Bender et al. (2010) predicted a decrease in the total number of tropical cyclones, but of the storms that do manifest they predicted a doubling of category 4 and 5 storms by the end of the twenty-first century. The largest increase was projected to occur in the Western Atlantic, north of 20° N. However, not all of the individual models showed such an increase (Bender et al. 2010).

In addition to changes in severe storm activity, climate models indicate that the environment will be less favourable for development of weaker storms (Vecchi & Soden 2007); thus, there may be fewer storms overall (Knutson et al. 2010). This has the potential to affect water supplies because the weaker storms, which now are much more frequent than what is predicted under future climate scenarios, are an important source of rainfall for coastal regions. However, rainfall may increase by as much as 20% in an individual storm (Knutson et al. 2010), leading to larger, short-term pulses of fresh water.

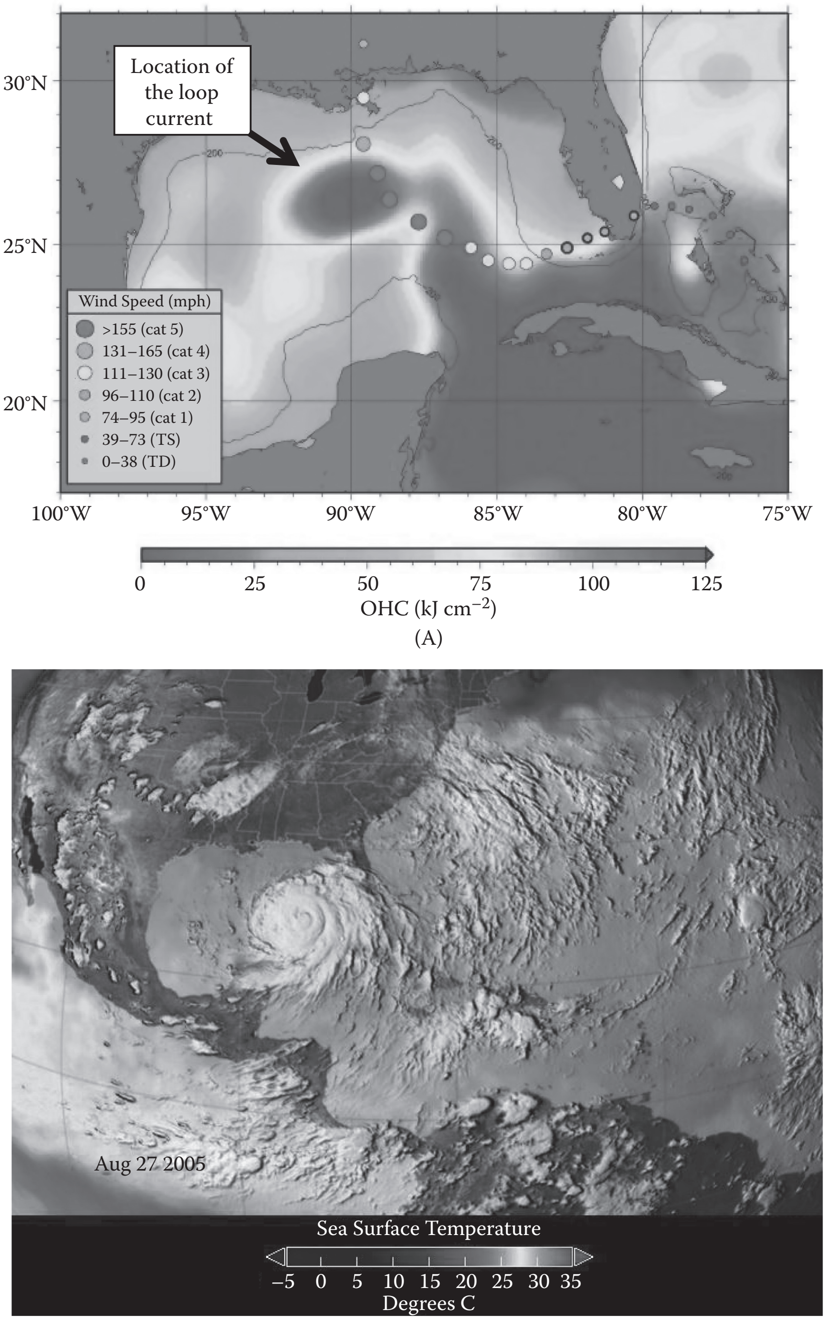
During a tropical storm, strong surface winds not only take heat out of the ocean but also mix the ocean at depths from tens to hundreds of metres, cooling the surface and creating a cold wake (Walker et al. 2005, Trenberth & Fasullo 2007, Trenberth et al. 2007). Hence, tropical storm activity depends not only on sea-surface temperatures but also on subsurface temperatures; this is especially important for setting the stage for the next storm and thus an entire active season. Better understanding of these feedbacks should improve ocean model predictions of hurricanes. However, surface fluxes are highly uncertain for strong winds, and the roles of ocean spray and ocean mixing are also uncertain. An example of this theory that is already occurring naturally is in the case of the warm and deep ‘Loop Current’ in the Gulf of Mexico, which appeared to play a key role in the intensification of Hurricanes Ivan (e.g., Walker et al. 2005), Katrina (Figure 5), and Rita (Trenberth et al. 2007).

Storm events in the Aleutian Islands are already having an impact on marine fisheries, commerce, and coastal ecosystems. In November 2011, the worst storm in 40 years hit the Alaskan coast, with hurricane-strength winds and large storm surges (Ulbrich et al. 2008). The increasing frequency of extreme events may be amplified by the loss of sea ice, which typically buffers the effect of winter storm surge on Alaskan coastlines. In addition, added heat to the lower atmosphere can generate storms in newly ice-free areas (Inoue & Hori 2011), as well as have impacts over larger regions (Overland et al. 2011).

Though modelling projections for climate change and storms predict fewer storms overall, a small increase of the most destructive storms will have a large impact because (1) damage increases exponentially with wind speed; (2) coastal population and infrastructure will increase over the coming century, resulting in greater vulnerability to strong storms; (3) storm surge has historically been responsible for the greatest loss of life; and (4) expected rise in sea level will likely produce greater storm surges.

Ocean circulation

Wind, heat, and freshwater fluxes at the ocean surface, together with tidal and other energy sources, are responsible for global ocean circulation, mixing, and the formation of a broad range of water masses. On the global scale, individual shallow and deep-ocean currents form an interconnected pattern known as the thermohaline circulation (THC), sometimes referred to as the ‘global conveyor belt’ (Broecker 1991). The path of the THC is generally described as originating in the Northern Atlantic Ocean, where cold, dense water sinks and travels across ocean basins to the tropics, where it warms and upwells to the surface. The warmer, less-dense, tropical waters are then drawn to polar latitudes to replace the cold, sinking water. However, in practice, the THC interacts with other currents, and mixing occurs among the waters travelling along these intersecting pathways, creating a more complex situation (Broecker 1991). The THC plays an important role in transferring heat from the oceans to the atmosphere, causing the water to become colder and denser, thus renewing the cycle (Lumpkin & Speer 2007, Kanzow et al. 2010). The THC is responsible for much of the



(A)

(B)

Figure 5 (See also colour figure in the insert) Ocean heat content and sea-surface temperature during Hurricane Katrina. (A) The ocean heat content in the prestorm environment for Hurricane Katrina. The storm intensity and position are indicated by the circles. (Modified from Mainelli et al. 2008.) (B) This image was created from AMSR-E data on NASA's Aqua satellite and shows a 3-day average of actual sea-surface temperatures (SSTs) for the Caribbean Sea and Atlantic Ocean, from 25–27 August 2005. Yellow, orange or red areas are 82°F or above (80°F is needed to maintain hurricanes). The position of Katrina is from 27 August. (From NASA Goddard's Scientific Visualization Studio.)

distribution of heat energy from the equatorial oceans to the polar regions and has a large influence on Earth's climate.

It is possible that the THC may weaken by the end of the twenty-first century as a result of climate change (Bindoff et al. 2007). Melting of polar ice will reduce the salinity and thus density of polar waters, which could weaken the rate at which this water sinks, possibly impairing circulation (Hu et al. 2011). However, there is large uncertainty related to the quantity of freshwater input necessary for such slowing of the THC (Kuhlbrodt et al. 2009). The pattern of temperature change as a consequence of THC slowing is complex, with predicted cooling over the North Atlantic (Wood et al. 2003, 2006, Vellinga & Wu 2004) and warming occurring further east (Stouffer et al. 2006). Another possible impact of weakening circulation may be increases in sea-level rise as a result of circulation-induced pressure gradients (Sturges 1974), especially on the East Coast of the United States, where models predicted a possible sea-level rise of 20 cm above and beyond what is predicted as a result of thermal expansion and glacial melt (Yin et al. 2010).

The following is a brief overview of possible impacts of climate change on two ocean current systems, the California Current and the Gulf Stream. Additional currents important to the United States (such as the Alaska Current) may also experience changes in behaviour as a result of climate change but are not discussed here.

California Current

The California Current spans strong physical gradients in circulation and water column structure (King et al. 2011). There is considerable evidence for physical changes, including significant warming and concomitant changes in water column stratification across the California Current over the past century (Palacios et al. 2004). For example, declines in oxygen concentrations due to changes in upwelling have already been measured along the coasts of California, Oregon and Washington (Grantham et al. 2004, Bograd et al. 2008, Chan et al. 2008). Despite this finding, climate-related effects on the California Current are highly uncertain. Some observations indicate that upwelling events are becoming less frequent, stronger, and longer in duration in accordance with climate change, with consequences for primary productivity along the US West Coast (King et al. 2011). Others suggest only moderate oceanographic changes, such as mild surface warming accompanied by relatively minor increases in upwelling-favourable winds in northern portions of the California Current, proposing that natural variability may overshadow climate change signals (Wang et al. 2010). Determining if the observed changes in upwelling reflect anthropogenic changes in variability of the California Current climate system and determining the possible impacts of climate-driven delayed onset of upwelling on future regional oceanic production in the California Current (Di Lorenzo et al. 2005) have emerged as two critical questions for further research.

Gulf Stream

The waters of the Gulf Stream travel from the Gulf of Mexico, pass through the Straits of Florida, travel off the US coast, and move through the Mid-Atlantic Bight until reconnecting to the coast at the Grand Banks off Newfoundland. Long-term observations of the Gulf Stream exist at only a few locations along this path. As stated, numerical climate models have projected slowing of the THC in the Atlantic over the next several decades. The Gulf Stream is one component of the THC, so this slowing could result in a potential reduction in Gulf Stream strength. However, the Gulf Stream is also influenced by the subtropical wind-driven gyre, and the possibility cannot yet be excluded that a slowdown of the THC might be accompanied by an increase in the wind-driven gyre, leading to no net impact on the Gulf Stream. If the Gulf Stream were to decrease in strength, there might be a rise in sea level along the US eastern seaboard as a result of relaxation of the pressure gradient associated with the Gulf Stream (Kelly et al. 1999). A decrease in the Gulf Stream volume and heat transport might also have significant impacts on precipitation patterns, hurricane tracks, and surface air temperatures throughout the Northern Hemisphere. The long-term variations of the Gulf Stream are not yet completely understood, warranting future observation and study.

Climate regimes

Regime shifts refer to a broad set of often-basinwide changes in the characteristic behaviour of the physical environment, such as persistent increases in ocean and atmospheric temperatures or shorter-term perturbations related to climatic events. These shifts have impacts on climate conditions in oceans and on land. Climate change and the subsequent warming of the atmosphere and oceans will likely have an impact on regional climate regimes, such as those encapsulated by the NAO, PDO, and ENSO. However, the nature of these oscillations over varying timescales creates challenges for climate prediction models, resulting in a moderate level of uncertainty with regard to climate change impacts. Climate model outputs are routinely used in a variety of climate change impact studies and assessment products, including the reports of the IPCC. There are, however, a number of global climate model limitations that must be carefully considered when interpreting and assessing uncertainty in regional climate-marine ecosystem impact studies (Stock et al. 2011). Establishing a clear set of considerations for assessing uncertainty in regional climate change impact assessments is vital for enabling an informed response to potential climate risks to Earth's oceans on multidecadal-to-century timescales.

The following is a brief overview of possible impacts of climate change on three climate regimes, the NAO, the PDO, and the ENSO. Additional regimes important to the United States (such as the North Pacific Gyre Oscillation) may also experience changes in behaviour as a result of climate change but are not discussed here.

North Atlantic Oscillation

The climate of the Atlantic region exhibits considerable variability on a wide range of timescales. A substantial portion of that variability is associated with the NAO (Stenseth et al. 2002), a measure of the fluctuation in the sea-level pressure difference between the Icelandic low (Stykkishólmur, Iceland) and the Azores high (Lisbon, Portugal). The NAO fluctuates between one of two states, positive or negative (Czaja et al. 2003, Arzel et al. 2011). When the NAO index is high (positive NAO state), there is an increase in precipitation over the eastern seaboard of the United States, and ocean temperatures are relatively warm. Conversely, when the NAO index is low (negative NAO state), decreased storminess, drier conditions, and relatively cool ocean temperatures occur in the eastern United States (Hurrell & Deser 2010). While the NAO index varies from year to year, it also exhibits a tendency to remain in one phase for intervals lasting more than a decade. An unusually long period of positive phase from 1970 to 2000 led to the theory that climate change was affecting the behaviour of the NAO (Goodkin et al. 2008). Uncertainty remains regarding whether climate change is influencing the timing of the NAO phases, but evidence indicates that the strength of its variability is increasing, as phases are becoming more strongly positive and negative (Rind et al. 2005).

Pacific Decadal Oscillation

The two principal modes of sea-surface temperature anomalies acting in the North Pacific Ocean are the longer-term PDO events, which occur on interdecadal timescales of roughly 25–30 years, and the shorter-term ENSO (discussed in El Niño/Southern Oscillation) events, which occur at a timescale of approximately 3–7 years (Mantua et al. 1997). The PDO, like the NAO, fluctuates between positive and negative phases. During the positive phase of the PDO, stronger-than-normal downwelling winds along the northern California and Alaska regions generate a local convergence of water masses at the coast that result in higher sea-surface height, warmer sea-surface temperatures, and anomalous polewards circulation near the coast (King et al. 2011). The opposite occurs during the negative phase. Overland & Wang (2007) suggested that under the A1B (middle range) CO_2 emission scenario, the change in winter sea-surface temperatures due to anthropogenic influences will surpass the natural variability in most of the North Pacific in less than 50 years.

El Niño/Southern Oscillation

The ENSO events exhibit a seesaw pattern of reversing surface air pressure and surface ocean temperature between the eastern and western tropical Pacific. The ENSO cycle is comprised of two interacting climate regimes, El Niño, which produces warmer sea-surface temperatures in the eastern Pacific, and La Niña, which produces cooler temperatures in that region. A balance of amplifying and damping feedbacks in ocean-atmosphere exchange controls year-to-year ENSO variability, and one or more of the physical processes responsible for determining the characteristics and global impacts of ENSO will likely be modified by climate change. For example, climate-driven changes in the upwelling cycle, with delayed and weak seasonal upwelling, have been documented in the central California Current region during El Niño years (Bograd et al. 2009). Higher-than-normal uplifting of the thermocline and strengthened polewards circulation in the proximity of the Southern California coast occurred during the most recent (2010–2011) La Niña event (Nam et al. 2011). These events influence ocean productivity, as well as atmospheric circulation, and consequently regional rainfall rates and extreme weather events at interannual timescales. However, despite considerable progress in our understanding of the potential impacts of climate change on many of the processes that contribute to ENSO variability, it is not yet possible to say whether ENSO activity will be enhanced or damped or if the frequency of events will be altered under climate change (Collins et al. 2010).

Carbon dioxide absorption by the oceans

The annual accumulation of atmospheric CO_2 has been increasing, and in 2010, global atmospheric CO_2 concentration was 39% above the concentration at the start of the Industrial Revolution in 1750 (Global Carbon Project 2011). The IPCC indicated that an 85% reduction in current CO_2 deposited into the atmosphere by the year 2050 would prevent exceeding a global mean temperature increase of 2.0°C, a temperature increase that could result in a tipping point toward extreme global changes (IPCC 2007). CO_2 reductions can be achieved both through reducing anthropogenic sources of CO_2 and supporting CO_2 uptake and storage through the conservation of natural ecosystems with high carbon sequestration rates and capacity (Canadell & Raupach 2008).

Ocean water holds approximately 50 times more CO_2 than the atmosphere, with the majority being held in the deeper, colder waters, but the ability of oceans to absorb CO_2 is not infinite. Currently, the oceans absorb more CO_2 than they release; however, CO_2 is less soluble in warmer waters, so as the sea-surface temperature increases, a decrease in oceanic uptake of CO_2 from the air is likely (IPCC 2007). CO_2 uptake also depends on the pH of ocean water, which decreases as more CO_2 is absorbed. Thus, as the pH decreases, so does the buffering capacity, or the ability of the ocean to continue to take up CO_2 (Revelle & Seuss 1957, Broecker & Takahashi 1966, Stumm & Morgan 1970, Skirrow & Whitfield 1975, Andersen & Malahoff 1977). However, future projections of oceanic sink strength and regional distribution are highly uncertain (Doney et al. 2009).

'Blue carbon' is a term used to describe the biological carbon sequestered and stored by marine and coastal organisms, with a significant fraction stored in sediments, coastal seagrasses, tidal marshes, and mangroves. Earth's marine and coastal ecosystems (mangrove forests, seagrass beds, salt marshes) are proportionately (on a per acre basis) more effective in sequestering carbon dioxide than are terrestrial ecosystems (Donato et al. 2011, McLeod et al. 2011, Fourqurean et al. 2012). When degraded or disturbed, these systems release carbon dioxide into the atmosphere or ocean. Currently, blue carbon sinks lose between about 0.7% to 7% of their area annually (McLeod et al. 2011). Global percentage cover of mangrove areas declined by 20% between 1980 and 2005

(Giri et al. 2010, Spalding et al. 2010). Carbon continues to be lost from the most organic soils in coastal areas. For instance, analysis of the agricultural soils of Sacramento's San Joaquin Delta, a diked and drained former tidal wetland, documents emissions of CO_2 at rates of 5 to 7.5 million tCO_2 each year, or 1% of California's total greenhouse gas emissions. Each year, an inch of organic soil evaporates from these drained wetlands, leading to a total release of approximately 1 billion tCO_2 over the past 150 years (Crooks et al. 2009, Deverel & Leighton 2010, Hatala et al. 2012). Similar emissions are likely occurring from other converted wetlands along the East and Gulf Coasts of the United States. Conservation and improved management of these systems bring climate change mitigation benefits in addition to increasing their significant adaptation value (Crooks et al. 2011, McLeod et al. 2011). Developing a better understanding of blue carbon science and ecosystem management issues has implications for future climate adaptation and mitigation strategies, as well as coastal habitat conservation.

Ocean acidification

Ocean chemistry is changing in response to the absorption of CO_2 from the atmosphere at a rate unprecedented over perhaps more than 50 million years (Hönisch et al. 2012). Ocean acidification refers to the decrease in the pH of Earth's oceans associated with uptake of atmospheric CO_2 and the subsequent chemical reactions. Ocean acidification is related to, but distinct from, climate change. However, it is important to include in this review because both climate change and ocean acidification share a common cause: increasing carbon dioxide concentrations in the atmosphere. Moreover, ocean acidification and climate change frequently have interactive effects on organisms and ecosystems. Particularly, ocean acidification has recently caught considerable attention as it affects the health of calcifying organisms and the rates of biogeochemical processes in the oceans (see reviews by Riebesell et al. 2007 and Doney et al. 2009). While its impacts on marine ecosystems have the potential to be severe, discussions regarding mitigation of CO_2 emissions and adaptation to climate change often ignore ocean acidification.

Surface waters of the ocean are estimated to have absorbed approximately 25% of all anthropogenically generated carbon since 1800 (Sabine et al. 2004). In the past, it was believed that the oceans would offset the effects of greenhouse gas emissions, but it is now understood that while absorption of CO_2 by oceans slows the atmospheric greenhouse effect, CO_2 reacts with seawater to fundamentally change the chemical environment of the oceans (Feely et al. 2010). Carbon occurs naturally and in abundance in seawater, simultaneously as a suite of multiple compounds or ions, including dissolved carbon dioxide [$CO_{2(aq)}$], carbonic acid (H_2CO_3), bicarbonate ions (HCO_3^-), and carbonate ions (CO_3^{2-}). The relative proportions of these compounds and ions adjust to maintain the ionic charge balance in the ocean (see the following steps).

Step 1: Air-sea exchange: $CO_{2(atmos)} \leftrightarrow CO_{2(aq)}$
Step 2: Hydrogen ion production: $CO_{2(aq)} + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-}$
Step 3: Production of calcium carbonate: $Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3$

Once uptake from the atmosphere by the oceans has occurred, aqueous CO_2 reacts with water to form carbonic acid (H_2CO_3); however, most of the H_2CO_3 disassociates to form hydrogen (H^+) and bicarbonate (HCO_3^-) ions. The hydrogen ions produced through this pathway lower the overall pH of the ocean and react with carbonate ions in the water to produce additional bicarbonate. The more hydrogen there is to react with carbonate ions, the fewer carbonate ions there are to produce calcium carbonate, a major building block for many shell-forming organisms. The average pH of the upper layers of the world's oceans has already declined by 0.1 units (from an average value of 8.2 to 8.1) over the past century. Given that pH is measured on a logarithmic scale, this represents a 30% increase in ocean acidity (Caldeira & Wickett 2003, 2005, Feely et al. 2004). Under current CO_2 emission rates, a further decline in pH of 0.3 to 0.4 units could occur by the year 2100 (Orr et al. 2005).

US ocean regions will respond differently to the rapidly changing carbon chemistry. Regions with strong upwelling regimes (such as the US West Coast) could be more vulnerable because upwelled waters are naturally higher in CO_2 (and thus lower in pH); these waters are already showing signs of anthropogenically augmented CO_2 levels (Feely et al. 2008). Coastal regions with high freshwater input (such as areas of the Chesapeake Bay) may also be more vulnerable to acidification because fresh water generally has a decreased ability to neutralize acids and may carry other acidifying solutes (Salisbury et al. 2008, Kelly et al. 2011). Ocean acidification will also be exacerbated in polar ecosystems (e.g., Arctic Ocean) because CO_2 is more soluble in colder water and the loss of sea ice in summer results in greater exposure of seawater to the atmosphere, allowing more exchange of CO_2 across the ocean–atmosphere interface. Freshwater dilution from ice melt at high latitudes also exacerbates acidification and results in undersaturation of carbonate minerals (Denman et al. 2011). Finally, predictions indicate that surface waters in the Arctic will be undersaturated with respect to aragonite, the more soluble form of calcium carbonate, as soon as within the next decade—sooner if other climate-related factors are taken into account (shrinking sea ice, increased fresh water) (Orr et al. 2005, Steinacher et al. 2009). Similarly, projections for the Southern Antarctic Ocean surface waters suggest that this region also is likely to become undersaturated with respect to aragonite by the year 2050 (Figure 6) (Orr et al. 2005).

Acidification can also be exacerbated by changes in oceanic circulation. The California Current has been identified as an area of particular concern because coastal upwelling brings to the sea-surface ‘deep older waters’ that are naturally low in pH. These deep waters carry the cumulative signature of decomposition of organic matter through respiration processes that have taken place over hundreds of years. When this very old water upwells in the California Current, it is naturally rich in CO_2 and has a high concentration of nutrients, low oxygen concentration, and low pH. Few measurements have been made of CO_2 and pH in upwelled waters of the California Current, but

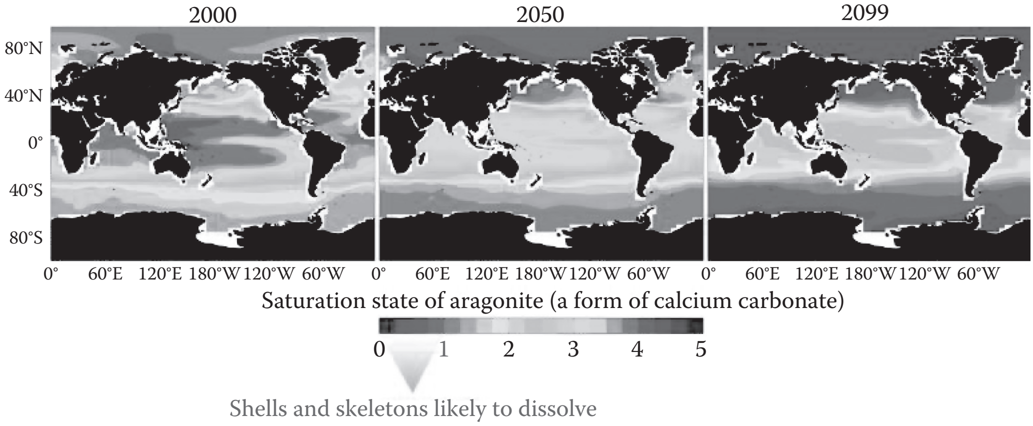


Figure 6 (See also colour figure in the insert) Aragonite levels predicted to drop as ocean acidifies. Calculated saturation states of aragonite, a form of calcium carbonate often used by calcifying organisms. Shades of red indicate areas where levels are so low that organisms may be unable to make new shells or skeletons and where most unprotected aragonite structures will dissolve. By the end of this century, polar and temperate oceans may no longer be conducive for the growth of calcifying organisms such as some molluscs, crustaceans, and corals. (Modified from Feely et al. 2009.)

available data indicate that upwelled waters are undersaturated with respect to aragonite and have a pH of 7.6 to 7.7 (Feely et al. 2008), values already lower than those expected for global oceans by 2100. This also makes the coastal and marine ecosystems of the US West Coast particularly vulnerable to the ocean acidification impacts described previously, as well as the impacts of ocean acidification on biological resources and ocean services shown to negatively affect oyster hatcheries in the US Pacific North-west.

It should be noted that low-latitude systems are not immune to such changes. In fact, the greatest rate of change in carbonate mineral saturation state has unfolded within the Atlantic tropical waters. Tropical water ecosystems will remain supersaturated with respect to aragonite for the foreseeable future (Feely et al. 2009); however, the effects of ocean acidification on marine organisms could also potentially manifest themselves in the form of tipping points, causing shifts in ecosystem dynamics. The location and likelihood of such events remain uncertain.

One of the more remarkable effects of the ocean's rapidly changing pH is the impact on low-frequency sound absorption (Hester et al. 2008). Sound is produced as a by-product of many anthropogenic activities (e.g., shipping, oil and gas exploration) and by natural sources (e.g., marine mammals, wind, earthquakes). A decline in pH of approximately 0.3 causes a 40% decrease in the intrinsic sound absorption properties of surface seawater (Hester et al. 2008). It has been suggested that sounds at frequencies important for marine mammals and for naval and industrial interests will travel some 70% farther with the reduction in ocean pH expected from a doubling of CO_2 (Brewer & Hester 2009). More recent modelling suggests, however, that due to the complexities of sound travel through the ocean, actual increases in background noise are likely to range from negligible (Joseph & Chiu 2010, Reeder & Chiu 2010) to a few decibels within the next 100 years (Udovydchenkov et al. 2010). With the magnitude of potential impacts uncertain and generating debate among researchers, the effect of ocean acidification on background sound levels in the ocean is an area that deserves further study.

Hypoxia

Hypoxia has been recognized as one of the most important water quality problems worldwide. The term *hypoxia* refers to a condition in which an aquatic environment has oxygen concentrations that are insufficient to sustain most animal life (Diaz & Rosenberg 1995, Vaquer-Sunyer & Duarte 2008) and can lead to 'dead zones'. The number of water bodies with recorded and published accounts of hypoxia from around the globe increased from fewer than 50 in the 1960s to approximately 400 by 2008 (Diaz & Rosenberg 2008). The number of water bodies in the United States with documented hypoxia follows the same trend, increasing from 12 prior to 1960 (Bricker et al. 2007) to more than 300 by 2008 (Committee on Environment and Natural Resources [CERN] 2010).

Hypoxia naturally develops when the water column becomes stratified, isolating an oxygen-depleted layer of bottom water and sediments (due to decomposition of organic matter) from a usually well-oxygenated surface layer (due to interactions with the atmosphere). Development and maintenance of hypoxic regions are strongly affected by water column mixing. Seasonal mixing due to temperature and tidal changes can destabilize stratification, leading to relatively abrupt mixing or 'turnover' of the water column that eliminates hypoxia. Hypoxia is especially threatening in estuaries, such as Mobile Bay, Alabama, and Pensacola Bay, Florida, which have low-amplitude tides (Hagy & Murrell 2007), as well as others, such as the Albermarle–Pamlico Estuarine System on the North Carolina coast, that are virtually tideless (Luettich et al. 2002) and therefore do not have as great a benefit from tidal mixing. These estuaries, which are also located in a warmer climate that results in warmer waters, are particularly susceptible to stratification and thus hypoxia (Reynolds-Fleming & Luettich 2004, Hagy & Murrell 2007, Park et al. 2007).

While hypoxia is a natural occurrence, human activities are exacerbating the frequency, duration, and intensity of hypoxic events (Cooper & Brush 1991, Helly & Levin 2004, Diaz & Rosenberg 2008). Eutrophication, an increase in the rate of supply of organic matter to an ecosystem, is most often associated with anthropogenic nutrient enrichment of coastal and ocean waters from urban and agricultural land run-off, wastewater treatment plant discharges, and air deposition of nutrients (Bricker et al. 2007, Galloway et al. 2008). Changes in precipitation patterns due to climate change, as stated previously, may have a significant impact on the amount of nutrients introduced to the marine environment through increased run-off. Eutrophication encourages algal blooms and subsequently the population growth of organisms that feed on algae; together, these organisms may utilize more oxygen than is being mixed into the water. This net loss of oxygen results in the development of hypoxic waters.

The second-largest eutrophication-related hypoxic area in the world (after the Baltic Sea, which is approximately 80,000 km^2) (Karlson et al. 2002, Hansen et al. 2007) occurs in the United States and is associated with the discharge from the Mississippi/Atchafalaya Rivers in the northern Gulf of Mexico (Alexander et al. 2008). The northern Gulf of Mexico hypoxic area has increased substantially in size since the mid-1980s, when it was first measured at about 4000 km^2 (Rabalais et al. 2007). In 2008, the ‘dead zone’ encompassed 20,719 km^2, the second largest hypoxic area on record for the Gulf of Mexico (CERN 2010). The most commonly reported eutrophication-related problems include hypoxia, losses of submerged grasses, excessive algal blooms, and numerous occurrences of nuisance and toxic harmful algal blooms (HABs; CERN 2010). Changes in temperature, precipitation, and winds will likely lead to long-term ecological changes that favour progressively earlier onset and duration of hypoxia each year.

Upwelling of nutrient-rich deep-ocean water into shallow areas can also support large blooms of phytoplankton (Chan et al. 2008) and may result in hypoxia. Climate-related changes in regional wind patterns might already be enabling the extent and severity of hypoxia off the coast of Oregon, a system dominated by upwelling (Chan et al. 2008). Subtler upwelling events have also been observed along the New Jersey coast and have been implicated in development of nearshore hypoxia (Glenn et al. 1996, 2004).

Climate change will almost certainly exacerbate both naturally occurring and eutrophication-related hypoxia, as well as the incidence of HABs. In general, the expected long-term ecological changes favour progressively earlier onset of hypoxia each year and, possibly, longer overall duration (Boesch et al. 2007). Increasing average water temperature is one mechanism by which climate change may increase susceptibility of systems to hypoxia. Higher water temperatures promote increased water column stratification, decreased solubility of oxygen, and increased metabolic rates for marine organisms, leading to increased oxygen consumption and nutrient recycling.

Climate predictions also suggest large changes in precipitation patterns, but with significant uncertainty regarding what changes will occur in any given watershed (Christensen et al. 2007). Increased precipitation can be expected to promote increased run-off of nutrients to estuarine and coastal ecosystems and increased water column stratification within these systems, contributing to more severe oxygen depletion (Justić et al. 2007, Karl et al. 2009). Climate predictions for the Mississippi River basin suggest a 20% increase in river discharge (Miller & Russell 1992), which is expected to increase the average extent of hypoxia on the northern Gulf of Mexico shelf (Greene et al. 2009).

A great deal of uncertainty remains about how rapidly the physical and chemical attributes of the oceans will change in the future, as well as the location and magnitude of specific impacts and what, if any, potential feedbacks will occur. The physical and chemical changes taking place in the global oceans set the stage for subsequent effects on marine organisms and US communities and economies dependent on marine services. Change to these systems may have larger consequences for US international partnerships and potential adaptation strategies.

Impacts of climate change on marine organisms

Climate change effects on marine organisms and ecosystems are occurring throughout the United States. These effects are occurring across scales, ranging from changes in physiology of individuals, to alterations in interactions between species, to ecosystem regime shifts. Climate-related impacts on ocean ecosystems include altered growth, reproduction, and survival; shifts in species phenology and ranges; increases in species invasions and disease; and changes in the abundance, productivity and diversity of marine plants and animals, among others. Observations and research have demonstrated high variability in the vulnerability and responses of organisms to changes in climate, resulting in 'winners' (i.e., species positively impacted) and 'losers' (i.e., species negatively impacted).

It is likely that these climate change effects on marine organisms and ecosystems will increase based on projected changes in the magnitude and variability of temperature, ocean pH, and other environmental parameters. These impacts are a result of both changes in average conditions and the occurrence of rare but extreme events. In addition, there may be unprecedented effects due to the complexity of marine ecosystems and the likelihood of non-linear interactions among stressors.

Climate change can serve as a threat multiplier, having an impact on marine organisms by interacting with non-climatic stressors, such as nutrient pollution and fishing pressure. While in many cases these 'multiple stressors' are simply additive in their impacts, synergistic (more than the sum of the individual effects) and antagonistic (less than the sum of the individual effects) interactions are also common. Scientific studies that address both climatic and non-climatic stressors can provide critical insight into these interactions and feedbacks. From a policy and management perspective, reducing non-climatic stressors (e.g., nutrient loading, habitat destruction, overharvesting) at local-to-regional scales can provide an opportunity to enhance the resilience of marine ecosystems to climate change and ocean acidification.

There is strong evidence that stressors can have both direct physiological effects on organisms and indirect effects through impacts on the species with which they interact. In addition, these responses are often non-linear, making threshold effects ('tipping points') an area of concern. Key to advancing knowledge and projections of change will be the sustained, long-term monitoring of ecological responses, with concomitant measurements of physical drivers and associated socioeconomic impacts. Research is also needed to improve understanding of the processes and mechanisms by which changing conditions affect organisms and ecosystems. Past and current responses of marine ecosystems to climate change can provide important insight into patterns, trends, and trajectories of change, and progress is being made in forecasting the ecological responses of ocean systems to climate change. However, the development of robust methods for projections into the future (including potentially novel environments) remains a challenge. Extrapolations to future responses must be made with caution given the likelihood of novel environments and the high uncertainty about the degree to which organisms can acclimate and populations can genetically adapt to climate-related changes. Thus, understanding the underlying mechanisms by which climate change and non-climatic stressors affect organisms and ecosystems is critical.

Physiological responses

The ability of marine organisms to grow, reproduce, and survive is affected by their environment, as well as by the other organisms and species with which they interact. Virtually all physiological processes are affected by an organism's body temperature (e.g., Somero 2011). Recent studies have also addressed the important impacts of ocean acidification (Hoegh-Guldberg et al. 2007, Widdicombe & Spicer 2008, Hofmann et al. 2010), alterations in salinity (Gedan & Bertness 2010, Lockwood & Somero 2011a), and changes in food resources (Lesser et al. 2010) on physiology. Physiological responses of marine organisms to environmental change include effects on growth (Menge et al. 2008) and metabolism (Jansen et al. 2007), survival (Jones et al. 2009), changes in the timing (Carson et al. 2010) and magnitude (Petes et al. 2008) of reproduction, as well as other consequences, such as increased susceptibility to disease (Mikulski et al. 2000, Anestis et al. 2010a). Importantly, climatic and non-climatic stressors, including pollution (Sokolova & Lannig 2008), physical disturbance (Bussell et al. 2008), and overharvesting (Hsieh et al. 2008, Sumaila et al. 2011), interact with one another, both in their physiological effects on individuals (Hutchins et al. 2007, Hofmann & Todgham 2010) and in their cumulative impacts on ecological communities (Crain et al. 2008, Pandolfi et al. 2011, Dijkstra et al. 2012). Thus, while considerable progress has been made in understanding physiological and ecological responses to climate change, and in making predictions about the likelihood of future physiological and ecological responses (Helmuth 2009, Mislan & Wethey 2011, Nye et al. 2011), additional work is needed to more clearly understand the impacts of the temporally and spatially complex changing environment on marine organisms and ecosystems. Advances in molecular technology offer one promising approach for improved understanding of the genetic underpinnings and physiological mechanisms associated with organismal stress responses (e.g., Trussell & Etter 2001, Dahlhoff 2004, Hofmann & Place 2007, Pörtner 2010, Tomanek & Zuzow 2010, Somero 2011, Tomanek 2011, Place et al. 2012).

One area of uncertainty is the ability of marine organisms to acclimatize, or populations to adapt locally, to new and rapidly changing environmental conditions (Trussell & Etter 2001, Bell & Collins 2008, Hofmann & Todgham 2010, Sorte et al. 2011). Some evidence exists for local adaptation of marine organisms to high-stress environments. For example, marine snails on the Oregon coast experience higher levels of aerial thermal stress (due to local environmental conditions experienced at low tide) than do southern populations of the same species in California (Kuo & Sanford 2009). Adult snails in Oregon have higher thermal tolerance than do their counterparts at cooler California sites, and they transmit this high tolerance to their offspring, suggesting that local populations have genetically adapted to the more extreme conditions that they experience (Kuo & Sanford 2009). Most research on local adaptation in marine systems to date has been conducted on organisms with fast reproductive cycles, such as microorganisms (Collins & Bell 2004, Bell & Collins 2008) and copepods (Kelly et al. 2012). Additional research is needed to elucidate better the potential roles of acclimatization and local adaptation to current and future change in marine environments (Schmidt et al. 2008, Kelly et al. 2012).

Effects of temperature change

Temperature has diverse effects on physiological processes in marine organisms (Somero 2011), including changes in metabolic rate (Jansen et al. 2007), as well as the functioning of critical enzymes and other cellular functions (Somero 2011). Thermal stress can lead to an increase in metabolic oxygen demand by organisms and ultimately to oxygen deficiency at the cellular level (Pörtner & Farrell 2008, Pörtner 2010). Metabolic oxygen deficiency has already been documented in commercially important species (e.g., Atlantic cod; Sartoris et al. 2003, Pörtner et al. 2008) and may become increasingly problematic in the future as increasing ocean temperatures are expected to exacerbate ambient low-oxygen concentrations through decreased oxygen solubility and increased oxygen demand by algae (Hofmann et al. 2011).

All organisms display tolerance limits that, when exceeded, lead to impacts on metabolism, growth, reproduction, or survival. Endothermic (i.e., 'warm-blooded') organisms (e.g., mammals and birds) must maintain a relatively constant body temperature, and changes in the ambient temperature outside their preferred range therefore require additional expenditures of energy. If temperatures become either too warm or too cold to maintain body temperature within tolerable limits, sublethal and lethal effects can occur. For example, manatees living in Florida experience a cold stress syndrome when water temperatures fall below 20°C for several days; consequences can include emaciation, immunosuppression, and increased mortality (Bossart et al. 2002). A recent unusual mortality event occurred from January to April 2010, when a total of 480 manatees (70% of which were juveniles) were found dead, with greater than 50% of the mortality attributed to cold stress (Barlas et al. 2011) associated with a record-setting negative phase of the Arctic Oscillation (National Climate Data Center [NCDC] 2010). Increasing severity of extreme weather events or alterations in average winter or summer temperatures can have negative impacts on endothermic marine species, and repeated mortality events resulting from thermal stress can lead to population decreases.

The vast majority of marine organisms (other than birds and mammals) are ectothermic (i.e., 'cold blooded'): Their internal temperatures are driven by ambient environmental conditions. Some marine organisms already live close to or at their thermal tolerance limits, whereas others exhibit broad tolerances (Hochachka & Somero 2002, Somero 2011). Extreme or prolonged high- or low-temperature events can lead to sublethal effects, such as reduced growth and changes in the timing and magnitude of reproductive output (Petes et al. 2008, Anestis et al. 2010b, Dijkstra et al. 2012), as well as mortality (Harley 2003, Petes et al. 2007, Harley & Paine 2009). Elevated temperature has also been linked to risk of physical disturbance. For example, the dislodgement of mussels by waves may be increased, potentially because byssal threads, the animals' primary anchoring system, decay more quickly in warmer water (Moeser & Carrington 2006). Loss of mussels would translate into a reduction in local diversity because hundreds of invertebrate species rely on mussel beds for habitat (Smith et al. 2006). Declines in such physiologically vulnerable 'foundation species' may exacerbate the detrimental impacts of climate change on ocean ecosystems (Gedan & Bertness 2010). In contrast, warm-adapted species may increase in abundance and range as they are able to invade new territory due to warming temperatures (Urian et al. 2011).

Reef-building corals around the world, including those in US states and territories, have been negatively impacted by increasing water temperatures. Corals are among the most vulnerable organisms to even slight changes in temperature. When water temperatures exceed 'normal' summer extremes by as little as 1–2°C for 3–4 weeks (Gleeson & Strong 1995), corals eject their symbiotic dinoflagellates (zooxanthellae), on which most coral species depend for their metabolic requirements and the ability to form skeletons (Hoegh-Guldberg et al. 2007). This phenomenon, 'coral bleaching', is not necessarily immediately fatal, but it can lead to severe reductions in reef health and resilience (Figure 7) (Hoegh-Guldberg et al. 2007). If populations of zooxanthellae are unable to reestablish themselves within host coral tissue, corals often suffer mortality in the mid- to long term (Pandolfi et al. 2011). Corals that have recently bleached may also be more susceptible to disease outbreaks (Miller et al. 2009). While debate on the ability of corals to adapt to environmental stress still exists (Hoegh-Guldberg et al. 2011, Pandolfi et al. 2011), a recent report by the World Resources Institute (Burke et al. 2011) indicated that 75% of the world's coral reefs, including almost all of the reefs in Florida and Puerto Rico, are threatened due to the interactive effects of climate change, ocean acidification, and local sources of stress, such as nutrient pollution. The same report projected that roughly 50% of the world's reefs will experience severe bleaching due to thermal stress by the 2030s, and more than 95% by the 2050s, based on current trajectories of greenhouse gas emissions (Burke et al. 2011). Carpenter et al. (2008) suggested that one-third of all reef-building coral species are at risk of extinction due to the combined effects of climate change and local stressors. Loss of coral cover and reef 3-dimensional complexity leads to losses of the many species of associated fishes and invertebrates that depend directly and indirectly on corals for habitat and food (Graham et al. 2006, Idjadi & Edmunds 2006, Alvarez-Filip et al. 2009). Therefore, continued loss of coral reefs is highly likely to have cascading effects on diversity, structure, function, and the valuable ecosystem services on which humans depend (e.g., Mumby & Steneck 2011).

Interactions between thermal stress and food availability can also affect physiology. For some marine animal species, increasing food supply can result in higher levels of thermal tolerance (Schneider et al. 2010). It is anticipated that climate change will have an impact on individual nutrition status as prey species shift geographic and depth ranges, altering food web dynamics (e.g., Bluhm & Gradinger 2008; see Figure 8). These impacts could be either negative, in the cases

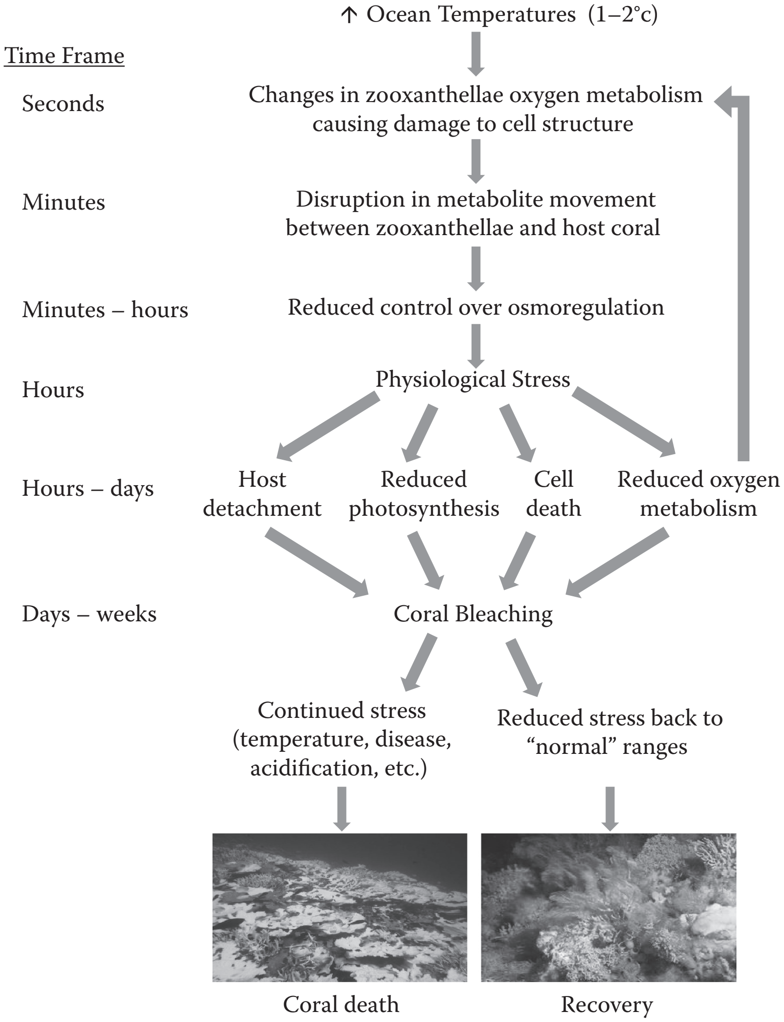


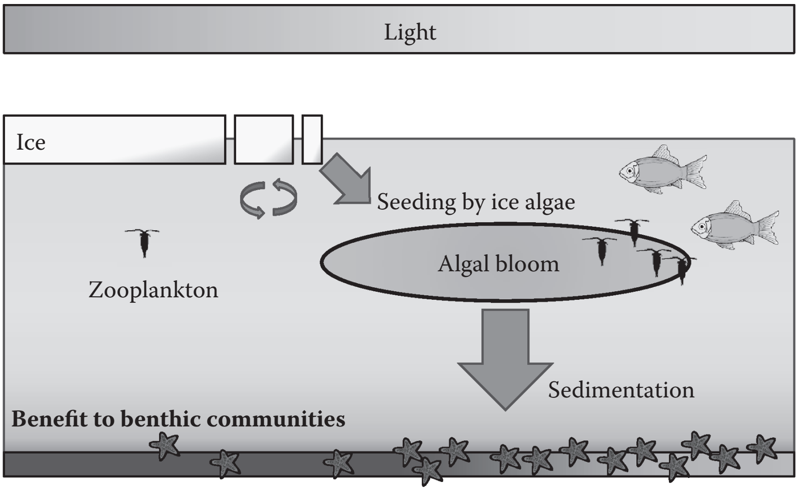
Figure 7 (See also colour figure in the insert) Physiological impacts of climate change on coral reefs. Impact of prolonged heat stress on the physiology of corals and their symbiotic zooxanthellae. (Modified from Mayfield & Gates 2007.)

of organisms that depend on specific prey items, or neutral or positive, for species that have generalized diets. Food depletion and resultant nutritional stress are well-known causes of immune suppression across several taxa (Burek et al. 2008). Increased exposure to unfavourable environmental conditions may exacerbate nutritional deficiencies, thus leaving individuals weakened and more susceptible to stress.

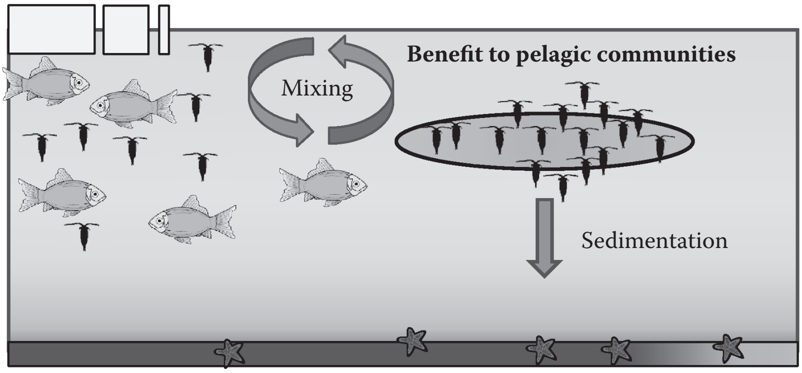
Ocean acidification impacts

Ocean acidification causes a reduction in the solubility in ocean waters of calcium carbonate, which many organisms use to create shells. Biological processes known to be affected by ocean acidification include calcification, photosynthesis, nitrogen fixation and nitrification, ion transport, enzyme activity, and protein function (Hutchins et al. 2009, Hofmann et al. 2010, Gattuso & Hansson 2011).

A growing number of laboratory and field studies have documented the negative impacts of ocean acidification on calcifying organisms (Fabry 2008, Doney et al. 2009, Gattuso & Hansson



(A) Current/late ice retreat



(B) Future/early ice retreat

Figure 8 (See also colour figure in the insert) Schematic representation of two scenarios that relate seasonal cycles of marine production to ice cover. (A) In years of abundant sea ice (and thereby cold surface waters), herbivorous zooplankton are less abundant early in the season and have little grazing impact on the ice algal and marginal ice zone blooms, resulting in primary production being largely exported to the benthic community. This supports a benthic-dominated food web, including bottom-feeding mammals and birds. (B) In years with less ice (and thereby warm surface waters), a later-occurring phytoplankton bloom dominates over sea-ice-related blooms. These phytoplankton blooms may be efficiently grazed by abundant zooplankton, which in turn are capable of supporting pelagic larval and juvenile fishes. (Modified from Bluhm & Gradinger 2008.)

2011). A recent meta-analysis (Kroeker et al. 2010) found an overall negative effect for the many types of organisms studied; however, when separated into taxonomic groups, the responses were variable. Physiological studies have likewise shown that organisms can vary greatly in their responses to decreasing pH, even among closely related species (Fabry et al. 2008, Doney et al. 2009, Ries et al. 2009, Hofmann et al. 2010, Byrne 2011). One challenge to enhanced understanding is that there are currently few natural modern analogs to a world under increased acidification (Hönisch et al. 2012). Therefore, recent studies have examined natural pH gradients surrounding underwater volcanic vents (Hall-Spencer et al. 2008, Fabricius et al. 2011, Porzio et al. 2011) and acidification in the fossil record (Ries 2010, Crook et al. 2011, Pandolfi et al. 2011, Hönisch et al. 2012) to gain insight into acidified conditions.

Although the biological implications of acidification for open ocean ecosystems remain an active area of research, some general trends are emerging. Calcification by the planktonic algal group coccolithophores, which form massive open-ocean blooms, will almost certainly be greatly reduced (Riebesell et al. 2000, Feng et al. 2008, Beaufort et al. 2011, Hutchins 2011), although responses to increased CO_2 do appear to vary between species (Fabry 2008). Zooplankton groups, such as Foraminifera and pteropods, that produce calcium carbonate shells will also be adversely affected (Orr et al. 2005, Moy et al. 2009, Lombard et al. 2010). Pteropods are an especially critical link in high-latitude food webs as commercially important species (e.g., salmon) depend heavily on them as prey items (Fabry et al. 2009).

In addition to calcification, another critical biogeochemical process that appears to be strongly inhibited by ocean acidification is nitrification. This process is a key link in the ocean's nitrogen cycle by which certain prokaryotes convert ammonia to nitrate, thereby making oxidized nitrogen forms available to marine biota (Beman et al. 2011). Nitrogen fixation rates of some dominant marine cyanobacteria increase substantially at low pH (Hutchins et al. 2007, Fu et al. 2008), as does cellular toxin production by some HAB species (Sun et al. 2011).

Certain species and ecosystems are particularly vulnerable to ocean acidification. Because coral skeletons are formed of calcium carbonate, the future of coral reefs under ocean acidification has received considerable attention. Studies have suggested that reef accretion stops at atmospheric CO_2 concentrations of 480 ppm (Kleypas & Langdon 2006), and climate models predict that at atmospheric CO_2 levels of 550 ppm, the worldwide dissolution of coral reefs is possible (Silverman et al. 2009). A study based on cores from the Great Barrier Reef in Australia showed that coral calcification rates declined 21% between 1988 and 2003 (Cooper et al. 2008). The observed decrease exceeds that predicted by changes in pH alone, suggesting potential effects of multiple and interacting stressors, such as ocean acidification, temperature, and nutrient stress (Cooper et al. 2008, Doney et al. 2009). Studies of reef communities at varying distances from natural CO_2 seeps have documented large declines in coral colony size, coral species richness, and coralline algae (the preferred settlement substrate of coral larvae) at low pH (Fabricius et al. 2011).

Research has also demonstrated the negative effects of ocean acidification on calcification by shellfish (Gazeau et al. 2007), particularly in areas such as the US Pacific North-west, where acidified waters caused wild oysters and oyster growers to suffer persistent production failures (Feely et al. 2008). Larval oysters are sensitive to the carbonate chemistry of the water, particularly as they transition from having no shell at all to having 70% of their mass consist of shell mineral material. During this period, there is a greater dependence on carbonate drawn from seawater, rather than from internal reserves, for shell carbon than during later stages. These results paint a picture of larval development that depends on favourable ambient conditions during critical and energetically expensive early-growth bottlenecks, with results that do not express themselves clearly until later in the organisms' lives. Hatchery managers who embrace quality measurement technology can optimize operations for favourable conditions or even control conditions with active manipulation of inflow water chemistry. Natural populations, however, will be subject to stress from additional acidification as CO_2 levels rise.

The geological past shows that the abundance and diversity of calcifying organisms are reduced when large amounts of CO_2 are released rapidly into the atmosphere (Zachos et al. 2005). However, this evidence is only partially helpful in understanding potential impacts of ocean acidification in the future, as even relatively abrupt geological changes in CO_2 levels in the past likely occurred over thousands of years, allowing the ocean enough time to buffer these increases chemically (Gattuso & Hansson 2011). The rate of acidification is much more rapid today (Gattuso & Hansson 2011), creating a magnitude of ocean change that is potentially unparalleled in at least the past approximately 300 million years of Earth's history (Hönisch et al. 2012).

Notably, to date, most studies of the physiological impacts of ocean acidification have been based on short-term experiments that range in duration from hours to weeks (Doney et al. 2009). Therefore, understanding the biological effects of chronic exposure to decreased pH and how ocean acidification interacts with other stressors in intact ecosystems remain relatively underexplored but critical areas of research.

Exposure to toxicants

Toxicants are poisonous substances that can be produced by organisms (biotoxins), released from geologic stores (e.g., heavy metals, some hydrocarbons), or result from a variety of anthropogenic sources, such as persistent organic pollutants, petroleum hydrocarbons, heavy metals, and radioactive substances (Burek et al. 2008). Climate change can alter toxicant exposure levels for marine organisms through changes in the distribution, frequency, and toxicity of HABs and other toxins. Climate-related changes can also occur through alterations in ocean currents that carry both toxicants and organisms into novel environments, increased precipitation that can lead to additional run-off of toxicants into estuaries, and changes in feeding ecology that propagate toxicants throughout the food web (Macdonald et al. 2005). Responses of marine organisms and ecosystems to changes in toxicant exposure are difficult to predict and will largely depend on the chemical features of the specific toxicants to which they are exposed (Segner 2011). Toxicant exposure levels may also change as animals alter their diets based on shifts in their prey items (Burek et al. 2008). Moreover, in an example of interactions between climatic and non-climatic stressors, organisms experiencing thermal stress may be more susceptible to the effects of contaminants (Schiedek et al. 2007).

Effects on life-history trade-offs and larval dispersal

Physiological trade-offs occur when resources are limited as each organism has a certain amount of energy available to maintain physiological processes, such as growth, reproduction, metabolism, and immune function (e.g., Roff 1992, Stearns 1992). The production of gametes and offspring, which is energetically costly, may therefore be compromised under stressful conditions as energy is redirected toward defence and survival mechanisms (Wingfield & Sapolsky 2003). Evidence of these life-history trade-offs has been documented for US West Coast intertidal mussels, which exhibited reduced relative allocation of energy towards growth and reproduction and increased energy towards physiological defences under high-stress conditions (Petes et al. 2008). In the western North Pacific, differences in optimal temperatures for growth of larvae of Japanese anchovy (22°C) and sardine (16°C) lead to contrasting fluctuations in larval growth rates of these two species based on ambient temperature (Takasuka et al. 2007). Such preferences for thermal regimes create out-of-phase stock oscillations for anchovies and sardines off California; that is, when conditions are optimal for sardine growth, they are suboptimal for anchovies and vice versa (Chavez et al. 2003). Changes in water temperature may alter these oscillations and therefore the relative abundance of these species in the future.

Phenology, the timing of annual life-history events (e.g., migration, breeding) can provide valuable insight into the impacts of climate change. Thermal stress has been found to alter the timing of spawning events in marine organisms, leading to mismatches of larval production with the peak in phytoplankton that serves as their food supply (Philippart et al. 2003, Edwards & Richardson 2004, Durant et al. 2007). These mismatches can lead to starvation, lower growth and development rates, reduced survival probabilities, and decreased recruitment (Cushing 1996). Impaired reproduction can have large, negative consequences for population dynamics and, in the most extreme cases, can lead to species collapse (Beaugrand et al. 2003). Differential changes in timing of reproduction across biogeographic gradients can have subsequent effects on patterns of larval dispersal (Carson et al. 2010).

Exchange rates of adults, juveniles, larvae, and gametes determine levels of connectivity between populations and can drive both local processes and meta-population dynamics (Erlandsson

& McQuaid 2004, Gouhier et al. 2010). Over large spatial scales, larval supply can determine biogeographic range boundaries (Herbert et al. 2009) as well as the colonization and spread of invasive species (US Environmental Protection Agency [EPA] 2008, Zardi et al. 2011). Thus, changing patterns of oceanic circulation are likely to have a significant influence on the ecology and population genetics of marine organisms. Temperature-dependent metabolism leads to an inverse relationship between temperature and the duration of planktonic larvae in the water column, suggesting that some species may develop more quickly under elevated temperatures, spending less time as larvae in the water column and therefore potentially dispersing shorter distances (O'Connor et al. 2007). On the other hand, faster growth and developmental rates under increased temperatures may increase survival probabilities through the larval stage (Hare & Cowen 1997, Kristiansen et al. 2011), provided that prey resources are adequate to meet the elevated energy requirements due to increased metabolism. Larval stages of some marine organisms are more vulnerable to stress than are their corresponding juvenile stages (e.g., Zippay & Hofmann 2010, Talmage & Gobler 2011) or adult (e.g., Matson & Edwards 2007). These findings emphasize the importance of considering the relative vulnerabilities of different life-history stages to climate change to understand and predict changes in future population sizes better (Russell et al. 2011).

Population and community responses

There is strong evidence that climate-driven changes in environmental conditions are affecting the survival, growth, and reproduction of diverse marine species, resulting in alterations in population sizes, which in turn affect marine community dynamics. Shifts in the distribution of many marine species that are consistent with changes in climate have been observed in coastal waters of all US regions. In general, warm-adapted species are moving polewards (e.g., Parmesan & Yohe 2003), although there is high variability in these responses due to the impacts of local environmental conditions, including non-climatic drivers (Helmuth et al. 2006a). Population size and distribution are also indirectly affected by climate-related changes in species interactions, such as competition and predation. In addition, strong evidence indicates that many marine species appear to be more vulnerable to disease when exposed to climate-related environmental stress, such as elevated ocean temperature. Collectively, these impacts are leading to observed changes in community composition and ecosystem processes. Exploring the relative sensitivity of marine species and their interactions to changing environmental conditions within an ecological context is key to advancing understanding and projections of future change.

Primary productivity

Marine primary productivity, by both microscopic and macroscopic photosynthetic organisms, forms the base of most of the ocean's food webs. The majority of marine primary producers are phytoplankton, a diverse suite of microscopic photosynthetic organisms. Macroalgae (i.e., seaweeds) and seagrasses are important primary producers that also provide nearshore habitat and food sources to diverse marine organisms. Shifts in primary productivity are frequently linked with patterns of oceanic circulation or changes in ocean temperature. Due to the complex linkages between air and water temperature, oceanic circulation, and atmospheric conditions, the consequences of climate change on primary productivity are often non-intuitive in both coastal and open-ocean systems. In the open ocean, primary productivity can be affected through the impacts of increased water temperatures on metabolic rates (increased productivity; e.g., Doney et al. 2012), as well as through increased stratification (decreased productivity; e.g., Behrenfeld et al. 2006). Warming can also lead to dominance by small-celled phytoplankton (picophytoplankton), reducing energy flow to higher trophic levels (Hare et al. 2007, Morán et al. 2010). A recent model projected changes in phytoplankton primary production, total density, and size structure for the North Pacific over the twenty-first century, with the dominant response being a shift towards smaller-size phytoplankton, which alters food chain length (Polovina et al. 2011).

It is uncertain whether marine primary productivity will increase or decrease under future climate change scenarios. On a global scale, a recent study suggested that the past several decades have shown an overall increase in marine primary productivity (Chavez et al. 2011). Primary productivity in the central and southern California Current system has increased over the past three decades (Chavez et al. 2011), correlated with increases in the intensity and duration of wind-driven coastal upwelling events (Garcia-Reyes & Largier 2010). In contrast, satellite-derived time series of chlorophyll have shown significant changes in phytoplankton, notably that the most chlorophyll-poor areas have been expanding (McClain et al. 2004, Behrenfeld et al. 2006, Polovina et al. 2008, Irwin & Oliver 2009), indicating reductions in primary productivity. Comparing the output from different earth system models, Steinacher et al. (2010) projected reductions in global primary production of 2–20% by 2100, with declines in mid-to-low latitudes due to reduced nutrient input into the euphotic zone, and gains in polar regions due to warmer temperatures and less sea ice. Additional observations, research, and modelling efforts will be necessary for improving understanding of the complex relationships between climate change and marine primary productivity.

Harmful algal blooms, of macroscopic and microscopic (single-cell) species, have been recorded on nearly all of the world's coastlines. Over the past 10 years, HABs have been reported in all major US coastal locales (Anderson 2012). HABs have increased in duration, number, and species diversity since the 1980s (Anderson 1989, 2009, Hallegraeff 1993) and can have large negative ecological and socioeconomic consequences. Some microalgal HABs cause direct impacts through production of toxins harmful or lethal to consumers, including shellfish, seabirds, and humans. Levels of cellular toxin production by some HAB species increase dramatically under high-CO_2 conditions, especially when growth is limited by nutrients (Fu et al. 2010, Sun et al. 2011); these findings have implications for increased HAB impacts in a more acidified, stratified future ocean. HABs involving the red tide organism *Karenia brevis*, a dinoflagellate that produces potent neurotoxins called brevetoxins, occur frequently along Florida's south-western coast, causing episodes of high mortality in fish, sea turtles, birds, bottlenose dolphins, and manatees (Gunter et al. 1948, Bossart et al. 1998, Flewelling et al. 2005, Kreuder et al. 2005, Landsberg et al. 2009). Although brevetoxin exposure increases during *K. brevis* blooms, the persistence of the toxin in the food web and the long-term effects of exposure on marine mammals are unclear (Fire et al. 2007). Blooms of 'nuisance' macroalgae may shade out other benthic primary producers (either seagrasses or perennial macroalgae) and negatively impact coral reefs through competitive interactions and reductions in coral larval settlement (Taylor et al. 1995, Lapointe et al. 2005, Hughes et al. 2007, Diaz-Pulido et al. 2011). In addition, when blooms of micro- or macroalgae senesce, their decomposition may cause large-scale mortalities of benthic and pelagic organisms due to lowered water-column oxygen levels (Deacutis et al. 2006, Lopez et al. 2008). When reef herbivores (e.g., fish and urchins that graze on macroalgae) are abundant and nutrient concentrations are low, corals are the competitive dominants on tropical hard bottoms. Local human activities tend to shift the competitive balance in favour of macroalgae at the expense of corals by removing herbivores that would normally keep macroalgal abundance relatively low. Increased nutrient levels in coastal waters can also favour macroalgal growth and lead to stress in corals. On many reefs, these processes have already resulted in a phase shift, which may be sudden or gradual, from coral-dominated reefs to algal-dominated reefs (Hughes et al. 2010).

There are many potential mechanisms responsible for the expansion of algal blooms into new areas and their extended duration in pre-existing areas. Increased nutrient inputs, such as those resulting from sewage treatment plants and fertilizer run-off, may be partially responsible for increases (Valiela et al. 1997, Teichberg et al. 2008, Thornber et al. 2008), whereas reductions in nutrient inputs may result in decreases in bloom density (Johansson 2002). Although nutrient increases (i.e., eutrophication) are not responsible for all HAB events (Anderson 2009, 2012), it can be difficult to separate the relative and interacting effects of eutrophication and climate change on HABs (Heisler et al. 2008, Rabalais et al. 2009).

Macroalgae and seagrasses can be important primary producers in shallow coastal waters. Kelps are among the largest and most conspicuous macroalgae, supporting some of the most diverse and productive ecosystems along the US coast (Mann 1973, Dayton 1985, Graham et al. 2008), primarily due to the provision of energy and complex habitat by the kelps themselves (Graham et al. 2007). Climate change is affecting the productivity of kelp forests across a variety of temporal and spatial scales, providing insight into macroalgal responses. Climate-induced variability in kelp distribution and abundance can affect the distribution of associated kelp forest fauna (Holbrook et al. 1997, Harley et al. 2006), as well as the productivity and diversity of kelp-associated communities (Dayton 1985, Graham 2004).

Most studies of the effects of annual-to-decadal variability of environmental factors on kelp systems have focused on the impacts of rising water temperature (and the generally concomitant decrease in coastal upwelling) on their growth and survival (Dayton et al. 1999, Broitman & Kinlan 2006, Reed et al. 2008). Shorter (e.g., 1-month) periods of exposure to anomalously warm, nutrient-poor ocean conditions can cause deterioration of kelp biomass, whereas prolonged (e.g., yearly-to-decadal) exposure to such conditions can lead to high mortality and distributional shifts of kelp taxa (Schiel et al. 2004). In some kelp systems, a shift may occur in the identity of the dominant kelp taxa according to species-specific environmental tolerances (Schiel et al. 2004), whereas in other systems, kelps and their associated communities may disappear altogether, resulting in an alternative habitat state (e.g., the formation of sea urchin barrens; Ebeling et al. 1985, Harrold & Reed 1985, Ling et al. 2009). Although the global response of kelp systems to rising temperatures (and decreasing nutrients) may appear ubiquitous, the specific response in any given region will depend on the biogeography and environmental tolerances of the local kelp taxa (e.g., Martínez et al. 2003, Wernberg et al. 2010, 2011a, Merzouk & Johnson 2011). Monthly-to-decadal climate-related changes in wave disturbance can also have dramatic negative impacts on kelp forest distribution, abundance, and structure (Dayton et al. 1999, Reed et al. 2008, Byrnes et al. 2011). Furthermore, it has been predicted that kelp systems will be similarly impacted by changes in ocean conditions over millennial timescales, with kelp forest optima occurring during cool, nutrient-rich, and well-illuminated periods (Graham et al. 2010).

Local-to-regional scale variability in ocean pH and both atmospheric and oceanic CO_2 concentrations are also likely to affect macroalgae and their associated communities, yet direct studies of these environmental impacts are generally lacking. The survivorship of calcified macroalgae, which are present in temperate and tropical habitats throughout US coastal waters, is greatly reduced under ocean acidification scenarios (e.g., Anthony et al. 2008). The combined impacts of ocean acidification and warming can increase skeletal dissolution rates (Diaz-Pulido et al. 2012) or lead to necrosis (Martin & Gattuso 2009) for calcified macroalgae. In contrast, non-calcified macroalgae may have higher tolerance to ocean acidification (Diaz-Pulido et al. 2011). While one study suggests that certain kelp life-history stages may be sensitive to ocean acidification (Roleda et al. 2012), others predict enhanced seaweed performance with rising CO_2 concentrations (Harley et al. 2006, Connell & Russell 2010). Canopy-forming kelps that can directly access atmospheric CO_2 may be particularly sensitive to increases in CO_2 concentrations, but the degree of carbon limitation in kelps is relatively unstudied (Harley et al. 2006). The impacts of ocean acidification and other stressors on calcified and non-calcified macroalgae are an important opportunity for future research.

Shifts in species distribution

Climate-related changes have been shown to influence the local and geographic ranges of many marine species (Hoegh-Guldberg & Bruno 2010, Burrows et al. 2011). Analyses of shifts in species distributions have demonstrated that marine systems appear to be changing substantially faster than terrestrial ecosystems (Helmuth et al. 2006b, Sorte et al. 2010a, Burrows et al. 2011). Studies have shown range shifts in response to both gradual changes in the environment (Findlay et al. 2010, Lockwood & Somero 2011b), as well as the lasting, sometimes multidecadal, impacts of rare-but-extreme events (Denny et al. 2009, Harley & Paine 2009, Firth et al. 2011, Wethey et al. 2011). Climate-related shifts often occur at range boundaries, but due to the importance of local environmental factors (Helmuth et al. 2006a, Burrows et al. 2011), responses such as decreased growth and increased physiological stress and mortality can also occur well within a species' range boundaries (Harley 2008, Place et al. 2008, Beukema et al. 2009). As temperatures warm, current range limits at polewards range boundaries may shift, and warm-adapted species (including certain invasive species) may become able to invade new territory (Urian et al. 2011). Forecasts of future responses to climate change based on observations of present-day changes and on knowledge of physiological responses strongly suggest that changes in species distribution will continue (Runge et al. 2010, Nye et al. 2011). As indicated, the pace and precise location of these changes remain uncertain due to the interactive effects of multiple stressors, the species-specific effects of these changes on interacting organisms, spatial and temporal heterogeneity in environmental drivers, and the ability of organisms to acclimatize or adapt to changing conditions (Sagarin & Gaines 2002, Denny et al. 2009, Nye et al. 2011, Sanford & Kelly 2011).

Evidence of temperature-driven shifts in species ranges is emerging across diverse marine primary producers and invertebrates. Temperature increases are already thought to be altering the distributions of major phytoplankton groups, with numerous observations of polewards range extensions for temperate species (Peperzak 2003, Merico et al. 2004, Hays et al. 2005, Cubillos et al. 2007, Hallegraeff 2010). Jones et al. (2009) reported high mortality of US East Coast intertidal mussels at their southern range boundary in North Carolina as a result of warming temperatures between 1956 and 2007. A study of the marine snail *Kelletia kelletii* in California demonstrated that the northern range boundary had extended northwards by over 400 km between the late 1970s and early 1980s, the first recorded extension north of Point Conception (Zacherl et al. 2003). This distributional shift was consistent with an observed gradient in seawater temperature and the confluence of two major ocean currents. A study using trace-elemental fingerprinting of larval mussel shells demonstrated autumn polewards movement and spring equatorwards movement in the larvae of two species of mussels on the coast of California (Carson et al. 2010). These results suggest that effects of climate change on larval dispersal due to changes in currents and alterations in the timing of reproduction may lead to shifts in species distributions. Temperature change is also leading to shifts in depth distributions of benthic invertebrates. For example, water temperature increases can be particularly acute in shallower, nearshore waters and have led to shifts of surf clams into deeper, cooler waters (Figure 9) (Weinberg 2005).

Climate change can also affect the distribution and abundance of marine fish species through diverse physical and biological processes and mechanisms, the relative importance of which varies across space and time (Ottersen et al. 2010, Overland et al. 2010). For example, fish stocks may shift geographically with changes in ocean temperature, oceanic circulation, or distribution of their prey (Humston et al. 2004, Hsieh et al. 2008, Barange & Perry 2009, Cheung et al. 2009; Figure 9). Climate-related shifts in the abundance and distribution of commercially important species can have consequences for associated fisheries (Cheung et al. 2010). Evidence of climate-induced shifts in the distribution of marine fish has been recorded in several regions of the US EEZ. Fodrie et al. (2010) documented changes in assemblages of fish within seagrass beds in the northern Gulf of Mexico between the 1970s and 2007, reporting the addition of numerous fish species that had previously not been observed. Nye et al. (2009) examined the spatial distribution of 36 species of marine fish found in the bottom trawl surveys of the National Oceanic and Atmospheric Administration (NOAA) along the continental shelf off the north-eastern coast of the United States from 1968 to 2007 and compared shifts to increases in bottom temperature. A significant polewards shift was

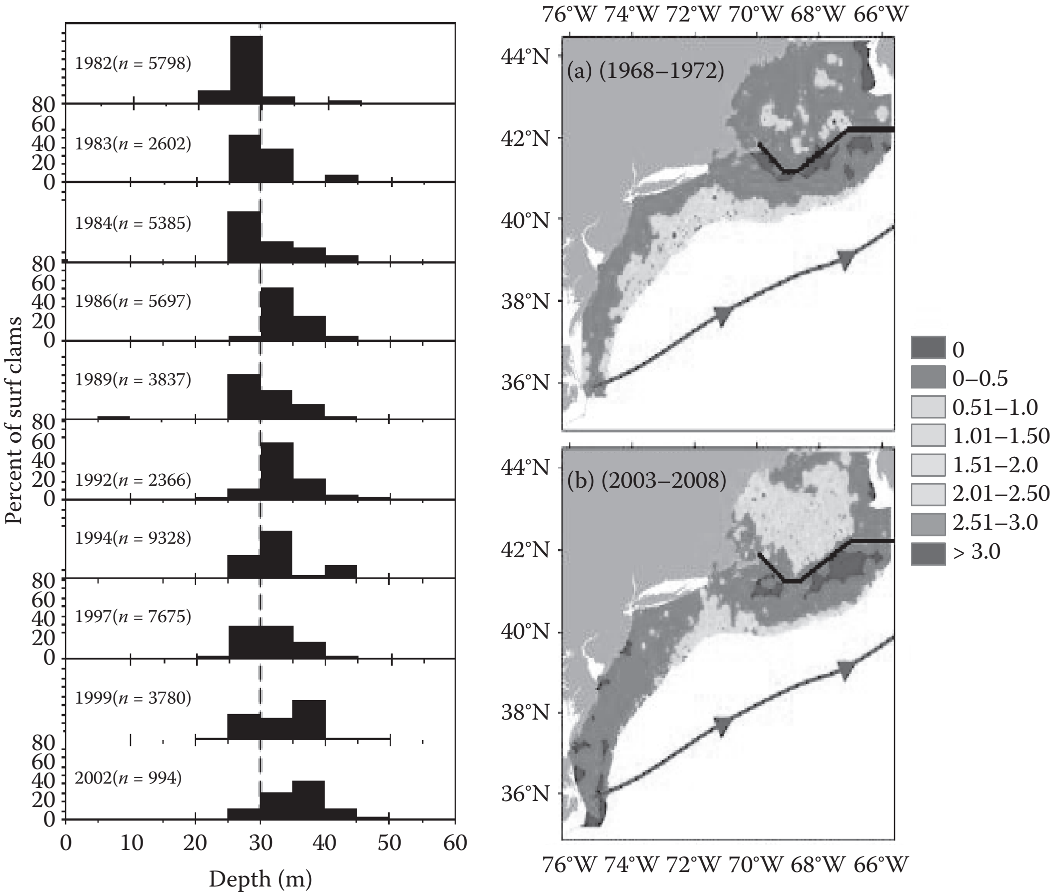


Figure 9 (See also colour figure in the insert) Changing spatial distribution for two marine species. Left: As water temperatures increase, an impact especially acute in shallower nearshore waters, surf clams have shifted their range into deeper, cooler waters. The graphs depict the percentage of surf clams captured at various depths (in 5-m intervals) from 1982 to 2002. *n* = Total number of surf clams captured (From Weinberg 2005. With permission from Oxford University Press.) Right: Changing spatial distribution of silver hake. (a) Past (1968–1972) and (b) recent (2003–2008) spatial distribution of silver hake biomass in the spring (March–May). Contoured colours represent the log weight (kg) per tow. Note the polewards shift in biomass. Inverse distance weighting was used to smooth the biomass of silver hake. The black line demarcates the boundary between the northern and southern populations of silver hake. The red line indicates the mean position of the Gulf Stream. (From Nye et al. 2011. With permission from Nature Publishing Group.)

found in 17 stocks, a southern shift in 4 stocks, and significant range expansion in 10 stocks (Nye et al. 2009). Shifts in the strength of the polewards undercurrent and ocean temperatures influence the spatial distribution of Pacific hake along the West Coast of North America, with a greater proportion of fish feeding off the coast of Canada in warm conditions (Agostini et al. 2006, 2007). It is unclear whether these shifts are responses to changes in oceanographic conditions or to changes in zonal and seasonal variations in the zooplankton community (Peterson & Keister 2003, Hooff & Peterson 2006). Shifts in thermal habitats and prey fields are expected to influence the distribution of Pacific tuna and other fish populations (Lehodey et al. 2003, 2010, Polovina 2007, Su et al. 2011). In the Arctic, where the rate and relative magnitude of change in ocean conditions is accelerated, differences in topography and currents suggest that there is a higher likelihood of range expansions from the Atlantic side than from the Pacific side (Sigler et al. 2011). These expansions are likely to occur in response to shifts in population density and productivity (Wassmann 2011). The ability of subarctic species to compete with species that are uniquely adapted to survive in the conditions of the Arctic is unknown.

Seabirds are also exhibiting shifts in species ranges, as well as changes in foraging behaviour resulting from shifts in prey distribution and abundance. For example, high ocean temperatures around Alaska's Pribilof Islands have led to prey shortages for least auklets (Springer et al. 2007). In the same region, reduced sea ice and increasing temperatures have led to breeding phenology shifts in kittiwakes over a 32-year period (Byrd et al. 2008). In addition, evidence indicates a possible range expansion of the razorbill in the Canadian Arctic in response to range expansion of favoured prey (Gaston & Woo 2008), as well as climate-related mismatches of prey availability and timing of breeding in thick-billed murres (Gaston et al. 2009).

Marine diseases

Over recent decades, there has been a significant increase in reported disease outbreaks in corals, urchins, molluscs, marine mammals and turtles (Ward & Lafferty 2004), and several disease-causing pathogens that were once thought only to occur on land are now known to have marine counterparts. The impacts of climate change on disease emergence and transmission are likely to act through a combination of several mechanisms, including host and pathogen range shifts, changes in contact frequency, changes in the proportion of individuals carrying disease vectors, introductions from terrestrial systems into marine environments, impacts on pathogen ability to reproduce, and increased environmental stress that leads to increased susceptibility of hosts to infection (Mills et al. 2010).

Evolved balances between disease agents, vectors, and hosts will likely be altered by climate change. In some cases, these changes could limit disease; in other cases, diseases could increase, particularly in stressed populations (Harvell et al. 1999, Altizer et al. 2003). Pathogens (macro- and microparasites) are in a constant state of change, and pathogen selection or alteration may affect host species or the course of an outbreak. Trends in infectious disease correlate with host-pathogen-environmental interactions, as either the host becomes more susceptible to disease or the pathogen's virulence increases. Variations in species' ranges may alter pathogen distribution, and warmer winters due to climate change can increase pathogen overwinter survivorship (Harvell et al. 2009). The protistan parasite *Perkinsus marinus*, which causes Dermo disease in oysters, proliferates at high water temperatures and high salinities. In oyster populations within Delaware Bay, epidemics followed extended periods of warm winter weather; these trends in time are mirrored by the northwards spread of Dermo up the eastern seaboard as water temperatures have warmed (Ford 1996, Cook et al. 1998). There is also evidence that increased water temperature is responsible for the enhanced survival of certain marine *Vibrio* bacteria, which can cause seafood-borne illness in humans (Martinez-Urtaza et al. 2010). Similarly, a survey of shell disease in American lobsters conducted in Massachusetts suggested that higher-than-average water temperatures between 1993 and 2003 led to increased disease prevalence (Glenn & Pugh 2006).

As terrestrial species expand their range or increased run-off from land occurs due to increased precipitation, pathogens novel to marine organisms can enter coastal and ocean systems. For example, faecal waste from the invasive Virginia opossum on the US West Coast has resulted in an increase in the spread of *Sarcocystis neurona*, a protozoan parasite that infects and kills marine mammals, including sea otters (M.A. Miller et al. 2010). In addition, the emergence and pathogenesis of the disease leptospirosis has been associated with environmental variability. Leptospirosis causes mortality of California sea lions (Gulland et al. 1996, Lloyd-Smith et al. 2007), as well as effects in harbour seals and northern elephant seals (Colegrove et al. 2005, Kik et al. 2006). Increased leptospirosis has been associated with increases in precipitation and flooding during El Niño events (Levett 2001, Storck et al. 2008). In Hawaii, increased cases of leptospirosis have been linked to flooding and have also shifted to wetter months of the year (Gaynor et al. 2007, Katz et al. 2011). *Leptospira* bacteria have been found to survive longer in fresh water and many of the sea lions stranded near freshwater estuaries, thereby increasing the possibility of transmission of the bacteria to domestic animals, terrestrial wildlife, or humans (Meites et al. 2004, Monahan et al. 2009, Zuerner et al. 2009). In the future, the combination of human population increase and urbanization, increasing populations and expansions of the ranges of marine mammals, and changes in environmental conditions such as extreme weather events, increased flooding, and increased temperatures may increase the exposure to and incidence of leptospirosis in both humans and marine mammals (Lau et al. 2010).

The impacts of climate change on future rates of marine disease are uncertain. Changes in environmental conditions may lead to range shifts of macro- and microparasites, but those shifts do not necessarily result in increased disease spread. New habitats may contain physical, physiological, or ecological (e.g., due to competition or predation) barriers to the spread of disease (Slenning 2010). As with their hosts, pathogens and vectors are susceptible to climate-related stressors (Lafferty 2009). Parasites that release gametes or larvae into the open marine environment or utilize intermediaries to complete various stages of their life cycle are particularly sensitive to climate change because their success is dependent on environmental conditions or on the availability and responses of their intermediate host species (Burek et al. 2008, Macey et al. 2008). Rising sea levels, warming ocean temperatures, and changes in ocean circulation and estuarine salinity may alter fish parasite composition and biogeography (Palm 2011). Reductions in non-climatic stressors provided by protected areas may potentially reduce disease prevalence. For example, a survey of 94 oyster reefs found significantly higher densities of oysters and significantly lower disease prevalence and severity inside sanctuaries (Powers et al. 2009).

In many cases, the lack of integrated, long-term data on marine diseases limits the ability to predict future climate-related changes in infection prevalence and intensity, emphasizing the need for enhanced and sustained surveillance. Pathogen discovery and identification is in a relatively nascent stage for marine systems. As molecular techniques become more accessible, source tracking is allowing scientists to better understand the connections between marine, terrestrial, and freshwater systems, as well as the evolution of marine pathogens. Improved understanding of these relationships will provide insight into current and future impacts of climate change on marine diseases.

Invasive species

Invasions by non-native species are widely recognized as significant threats to native biodiversity (e.g., Carlton 1996, Ruiz et al. 2000, Stachowicz et al. 2002a, Rahel & Olden 2008). The frequency of introductions has increased dramatically over the past two centuries, and species introductions have been documented in most marine habitats worldwide (e.g., Ruiz et al. 1999, 2000). San Francisco Bay is one of the most heavily impacted coastal systems, with over 230 non-indigenous species (Cohen & Carlton 1998). While only a fraction of invasive species have had significant impacts on established food webs and trophic linkages, their ecological and economic impacts can be profound.

The majority of marine species introductions are caused by shipping (ballast water and hull fouling) or fisheries effects (Ruiz et al. 2000), and invasions consistent with climatic drivers (e.g., changes in temperature) have also been reported (e.g., Reid et al. 2007, Firth et al. 2011). Climate-related impacts on tourism, commerce, and recreation could also create indirect effects on the frequency of invasions (Hellmann et al. 2008). Potential changes in shipping patterns and new routes resulting from loss of Arctic sea ice could lead to new introductions through ballast water or hull fouling (Pyke et al. 2008). In addition, climate change-induced shifts in the distributions of invasive species that are already established could lead to their movement into habitats that were previously uninvaded (de Rivera et al. 2011, Doney et al. 2012). For example, climate change is predicted to result in the movement of many planktonically dispersing, fast-growing Pacific species (e.g., molluscs) into Atlantic waters via the Bering Strait and Arctic Ocean (Vermeij & Roopnarine

2008), although existing physical and physiological barriers to movement (i.e., seasonal ice cover and cold bottom waters) indicate that the number of species capable of invading the polar region may be limited (Sigler et al. 2011). On the Florida coast, evidence suggests that northwards range shifts of the introduced Asian green mussel, *Perna viridis*, may currently be limited by cold temperatures (Urian et al. 2011). Therefore, increasing temperatures could potentially allow for range expansion of this invasive species (Urian et al. 2011).

Once species become established in new areas, climate change may facilitate their subsequent success (Hellmann et al. 2008) as many invasive species have wider temperature tolerance ranges than their native counterparts (Stachowicz et al. 2002a, Braby & Somero 2006, Sorte et al. 2010b, Abreu et al. 2011, Lockwood & Somero 2011b). Climate-mediated invasions and range shifts may also alter species interactions as superior competitors (Stachowicz et al. 2002a) and predators (Smith et al. 2011) move into temperate and polar latitudes. In addition, introduced species may affect the distribution of diversity among trophic levels; in several coastal food webs, introduced species have been at least partially responsible for community-wide shifts towards lower trophic levels (Byrnes et al. 2007). These consequences of invasions present a major threat to the persistence and interactions of native marine species in a changing climate.

Protected species

There is strong evidence that climate change is already affecting a variety of marine protected species, such as marine mammals, sea turtles, and seabirds, and it is likely that these impacts will increase in the future. The effects on these species are expected primarily from shifts in productivity and prey availability; changes in critical habitats, such as sea ice (due to climate warming) and nesting and rearing beaches (due to sea-level rise); and increases in diseases and biotoxins due to warming temperatures and shifts in coastal currents. Predicting the consequences of climate change on marine protected species is difficult due to the relative paucity of data and uncertainties regarding how they will respond if numbers and densities are reduced (Simmonds & Isaac 2007, Hoegh-Guldberg & Bruno 2010, Kaschner et al. 2011, Wassmann et al. 2011).

Many protected marine species are highly mobile or migratory, occupying and utilizing a wide range of habitats and resources throughout their life history. Animal migration is closely connected to climatic factors, and as a result, these species are in many ways more vulnerable due to the differential impacts they may experience at various life stages. For example, marine turtles may cross entire ocean basins throughout their lifetimes and can occupy diverse habitats, such as sandy beaches, mangroves, and seagrass beds (Musick & Limpus 1997, Hawkes et al. 2006, Polovina et al. 2006, Shillinger et al. 2008). In the Atlantic Ocean, warmer years would mean a stronger-than-average Gulf Stream current, helping juvenile turtles get to the North Atlantic Gyre and leading to increased productivity and population size. However, in the Pacific Ocean, loggerheads perform best under anomalously cold conditions. Therefore, available climate data indicate the potential for significant population declines of the Pacific population by 2040 due to warming temperatures (Van Houtan & Halley 2011). Projected increases in sea level and extreme event intensity, coupled with fortification of coastal areas, could erode shorelines and compromise the availability of suitable nesting beaches (Hawkes et al. 2009). In addition, increased beach temperatures have led to altered sex ratios (higher female-to-male ratios) in hatchlings of marine turtles, for which nest temperature determines the sex of offspring. In parts of the southern United States, hatchlings of loggerhead sea turtles are currently female biased, and even moderate further increases in temperature could lead to a severe lack of males (Hawkes et al. 2007), which can reduce population viability (Poloczanska et al. 2009). Anomalously cold temperatures can also affect turtles. Sea turtles along the US Atlantic Coast and Gulf of Mexico experience episodic, cold-stunning events when water temperatures drop below 10°C (Witherington & Ehrhart 1989, Morreale et al. 1992, Foley et al. 2007). During these events, hundreds of cold-stunned turtles float listlessly on the water or are washed on to shore. An open question remains regarding how temperature fluctuations, which are expected to increase under climate change, are likely to affect turtle populations (Neuwald & Valenzuela 2011), including sea turtles.

Changes in thermal regimes are affecting the abundance, distribution, feeding, and phenology of protected seabirds (Bertram & Kaiser 1993, Chastel et al. 1993, Montevecchi & Myers 1997, Grémillet & Boulinier 2009). For example, declines in oceanic productivity around the north-western Hawaiian Islands in the 1980s led to a 50% reduction in the survival of red-footed booby and red-tailed tropicbird eggs and chicks (Polovina & Haight 1999). Reduced productivity and warmer temperature in the South-east Farallon Islands (e.g., Sydeman et al. 2009), as well as low prey abundance (Sydeman & Thompson 2010), have led to delayed breeding and reduced offspring numbers in Cassin's auklet (Wolf et al. 2009). Wolf et al. (2010) have projected additional climate-related population declines of 11–45% by the end of the century. The common murre has also exhibited a declining trend in reproductive success in the South-east Farallon Islands, reflecting reduced availability of their preferred prey item (rockfish). In 2009, reproductive success of common murres was among the lowest observed in the previous 38 years and the lowest ever recorded during a non–El Niño year (Warzybok & Bradley 2010).

Warming water temperatures and loss of sea ice are fundamentally changing the behaviour, condition, survival, and interactions of Arctic marine mammals (Kovacs et al. 2010, Heide-Jørgenson et al. 2011, Thomas & Laidre 2011, Wassmann et al. 2011), and these changes are expected to continue. Cetaceans, including grey whales (Moore et al. 2003, Stafford et al. 2007, Moore 2008); orcas (Higdon & Ferguson 2009); and sei, fin, and minke whales (Norwegian Polar Institute Marine Mammal Sighting Data Base: http://www.npolar.no), have been sighted further north or at higher northern densities than normal. Similar impacts are occurring for pinnipeds; harbour porpoises are appearing in northern areas, and harp seals are being sighted in northern locations during abnormal times of the year (Norwegian Polar Institute Marine Mammal Sighting Data Base). Major declines in pup production and abundance have been documented for hooded seals in the North-east Atlantic, ringed seals in Hudson Bay, and harp seals in the White Sea (Ferguson et al. 2005, Chernook & Boltnev 2008). Polar bears are spending more time on land due to reduced ice cover, resulting in declines in survival, condition, body size, and reproductive rates (Stirling et al. 1999, Stirling & Parkinson 2006). In addition, landwards shifts of polar bear dens (Fischbach et al. 2007) and declines in the condition and survival of polar bear cubs have occurred (Regehr et al. 2006, 2010). Pacific walrus females and pups are also being forced to spend more time resting on land, and abandoned calves at sea suggest nutritional stress (Cooper et al. 2006, Garlich-Miller et al. 2011, Kavry et al. 2008) due to separation from feeding areas and the loss of sea-ice resting platforms (Kovacs et al. 2010). These examples illustrate some of the challenges facing marine protected species and their managers in a changing climate.

Ecosystem structure and function

Shifts in species distributions and interactions are also beginning to create novel, 'no-analog' ecosystems consisting of species with little or no shared evolutionary history (Hobbs et al. 2006, Williams & Jackson 2007), and it is likely that this will continue with unprecedented environmental change in the future. While progress is being made in forecasting future responses, complex, non-linear effects of changing environmental conditions on marine communities present additional uncertainty and challenges for managers (Crain et al. 2008).

Particularly problematic is obtaining an understanding of how complex feedback interactions between changes in the physical environment will affect ecological processes. Warming, ocean acidification, stratification, and other climate-related parameters can be both synergistic and antagonistic in their effects on marine organisms, making whole-ecosystem predictions difficult with the current state of knowledge (Boyd et al. 2008, Pörtner 2008, Hutchins et al. 2009, Hofmann et al. 2010). Ongoing research efforts are targeting these interactive, multistressor effects, but the fact that many environmental factors are simultaneously in flux makes accurate forecasting of ecosystem-level responses a challenging undertaking.

Species interactions and trophic relationships

Marine ecosystems are influenced not only by the direct effects of climate change on individuals and populations but also through indirect effects, as environmental change alters the strength of species interactions, including competition, predation, parasitism, and mutualism (reviewed by Kordas et al. 2011). These indirect effects can arise via different mechanisms.

Environmental change can alter an organism's physiology and behaviour and therefore its per capita effect on the species with which it interacts. Changing ocean temperature and chemistry can affect the per capita feeding rate of an individual consumer (Sanford 1999, Pincebourde et al. 2008, Gooding et al. 2009, O'Connor 2009) or modify an individual's competitive ability through effects on its growth rate (Stachowicz et al. 2002b, Wethey 2002, Sorte et al. 2010b). Differential impacts of thermal stress on predators and their prey can lead to altered species interactions (Yamane & Gilman 2009). For example, due to temperature-related effects on metabolism, exposure to warm water can increase the feeding rates of US West Coast sea stars (*Pisaster ochraceus*) on their mussel prey (Sanford 1999) until temperatures exceed thermal optima and feeding rates are reduced due to stress (Pincebourde et al. 2008). Studies have further shown that the interactive effects of increased water temperatures and increased aerial body temperature during low tide significantly affect rates of predation by *P. ochraceus*, in that these predators are more strongly affected by stressors that occur out of phase with one another, that is, when animals are constantly under stress due to elevated water and aerial temperatures (Pincebourde et al. 2012). Changes in hydrodynamic conditions can affect the ability of prey to detect predators, as has been shown by experiments examining the behavioural responses of whelks to predatory crabs under different flow conditions (Large et al. 2011).

Climate change alters species interactions via changes in the population density of interacting species. Environmental changes affect species differentially, and the resulting increases or decreases in population abundance can trigger chains of indirect effects (Poloczanska et al. 2008, O'Connor et al. 2009). For example, changes in ocean temperature and carbonate chemistry frequently alter the relative abundance of macroalgal species, which can in turn affect the abundance of herbivores that feed on them (Schiel et al. 2004, Kroeker et al. 2011). Often, a few key species interactions contribute disproportionately to maintaining community structure and ecosystem function (Paine 1992). For example, the saltmarsh grass *Spartina patens* reduces salinity stresses acting on species living within the plant canopy, and thus the removal of this structural species can have cascading effects on marsh communities (Gedan & Bertness 2010). If these interactions are sensitive to environmental conditions, they may act as 'leverage points' through which small changes in climate are amplified to produce large changes at the community and ecosystem levels (Sanford 1999, Kordas et al. 2011, Monaco & Helmuth 2011). Similarly, when the direct effects of climate change have a negative impact on the abundance of habitat-forming species such as coral, kelps, and mussels, there are often cascading effects on ecosystem function due to loss of the services that these foundation species provide (Schiel et al. 2004, Pratchett et al. 2008, Wootton et al. 2008, Wernberg et al. 2011b). Such rippling effects are often unpredictable due to the complexity of food webs (Schiel et al. 2004, Doney et al. 2012).

Climate-related shifts in the geographic distribution of marine species are altering biogeographic patterns of co-occurrence and interaction (Sorte et al. 2010a, Kordas et al. 2011). Analogous shifts in the vertical distribution of sessile intertidal prey species have increased their overlap with, and vulnerability to, predatory sea stars (Harley 2011). Similarly, as described previously, ocean warming can alter the timing of life-history events such as spawning, leading to temporal mismatches, or sometimes increased overlap, between consumers and their food sources (Philippart et al. 2003, Edwards & Richardson 2004, Kristiansen et al. 2011). Climate-related shifts in species dominance have also been observed throughout the United States, including the California Current, the Gulf of Alaska, the Bering Sea (Hare & Mantua 2000), and the North Atlantic (Auster & Link 2009). However, these shifts do not always result in changes in ecological processes. For example, Auster and Link (2009) found that while climate-induced shifts in species dominance were observed in the Georges Bank ecosystem, these often involved switching between species that occupied redundant roles within trophic guilds. This redundancy may buffer against ecosystem reorganization under climate change, but the extent of buffering is unknown in most systems.

Currently, the ability to project the impacts of climate change on trophic linkages within marine ecosystems is limited primarily to conceptual models of marine ecosystem organization (Hunt et al. 2011, King et al. 2011, Monaco & Helmuth 2011). As understanding of the range of complex responses of marine species to environmental disturbance improves and coupled biophysical models of marine ecosystems become available, the ability to predict with higher certainty the likely implications of climate change on marine ecosystems will be enhanced. In the near term, observations and monitoring systems provide the best method of detection and attribution of changes in the trophic structure of marine ecosystems and of validating models of population- and ecosystem-level responses (Helmuth et al. 2006b, Wethey & Woodin 2008, Helmuth 2009, Wethey et al. 2011). Integrated, sustained observations of the abundance, diets, distribution, and physiological condition of marine species, coupled with field and laboratory studies that identify species responses to ecosystem change, will be critical. There is a need to understand patterns of genetic variance (Trussell & Etter 2001, Schmidt et al. 2008), particularly that which underlies traits that influence susceptibility to environmental stress (Place et al. 2008). Over time, insight gained through these efforts will provide the data and understanding needed to more reliably model complex ecosystem responses to climate change.

Biodiversity

Several efforts have been implemented to document, quantify, and assess biodiversity of US marine ecosystems through initiatives such as the Census of Marine Life (e.g., Fautin et al. 2010) to gain baseline understanding and monitor changes through time. Climate-related distribution shifts have already altered community composition and biodiversity of many systems and taxa, including phytoplankton (Peperzak 2003, Merico et al. 2004, Hallegraeff 2010), pelagic copepods (Beaugrand et al. 2002), rocky intertidal invertebrates (Barry et al. 1995, Southward et al. 2005, Helmuth et al. 2006b, Wethey et al. 2011), fishes (Perry et al. 2005, Fodrie et al. 2010, Nye et al. 2009, Last et al. 2011), and seabirds (Hyrenbach & Veit 2003), among others. These changes in community composition are a function of both local extinction of species and invasions from elsewhere.

Ocean acidification is also affecting biodiversity and community structure in marine ecosystems. In a north-eastern Pacific rocky shore community, declining pH over 8 years corresponded with gradual shifts from the mussel-dominated communities typical of such temperate shores to communities more dominated by fleshy algae and barnacles (Wootton et al. 2008). Similarly, in shallow benthic communities near natural CO_2 seeps, calcareous corals and algae are replaced by non-calcareous algae, and juvenile molluscs are sharply reduced in number or absent altogether (Hall-Spencer et al. 2008).

Importantly, not only are levels of biodiversity affected by climate change but also levels of biodiversity can influence the resilience of marine ecosystems to climate change. Experiments show that more diverse communities tend to be more stable (i.e., less susceptible to disturbance and variability through time) (Jiang & Pu 2009). Analyses of global fisheries time series also support the hypothesis that marine biodiversity increases ecosystem stability and resilience to perturbations (Worm et al. 2006). Biocomplexity and diversity of fishes have been shown to decrease variability in stock productivity (Hilborn et al. 2003) and increase profitability to resource users (Schindler et al. 2010). Further research is needed to understand the causes and consequences of biodiversity change in marine ecosystems, including impacts on resilience, stability, and the provisioning of ecosystem services on which humans depend. Nevertheless, there is now sufficient evidence from a wide range of ecosystems to conclude with confidence that, on average, loss of biodiversity reduces ecosystem productivity and stability (Stachowicz et al. 2007, Cardinale et al. 2011).

If species cannot migrate or adapt to a changing environment, they face local or even global extinction. Humans have directly caused the global extinction of more than 20 described marine species, including seabirds, marine mammals, fishes, invertebrates, and algae—and many others have likely disappeared unnoticed (Sala & Knowlton 2006). Under projected climate change, marine species extinctions are expected to be most frequent in subpolar regions, the tropics, and semienclosed seas (Cheung et al. 2009). Cold- and ice-adapted species are especially vulnerable as ocean warming degrades their preferred habitats and invasions occur from temperate regions. For example, warming waters have recently allowed large lithodid 'king' crabs to invade the Antarctic shelf for the first time in 14 million years, where they have reduced benthic diversity and appear to have driven certain species locally extinct (Smith et al. 2011).

Quantitative estimates of species losses based on historical comparisons, measured and projected habitat loss, and demographic trajectories of wild populations suggest that Earth is now approaching (if not already in the midst of) the sixth mass extinction in its history, with rates of species loss two to five orders of magnitude above the average over geologic time (Pimm et al. 1995, Dirzo & Raven 2003, Pimm 2008, Butchart et al. 2010, Pereira et al. 2010, Barnosky et al. 2011). The principal drivers of the current extinction wave are habitat loss, overexploitation, pollution, and impacts of invasive species (Purvis et al. 2000), but changing climate has contributed to several mass extinction events in the past (Barnosky et al. 2011), and today's much more rapidly changing climate is expected to exacerbate the impacts of these other drivers in the coming century (Brook et al. 2008).

Regime shifts and tipping points

As a result of environmental and ecological complexity in responses to climatic and non-climate stressors, rapid changes in ecosystem structure and function are a particular area of concern. Evidence of rapid phase shifts (or regime shifts) is emerging across diverse US geographic locations and ocean ecosystems (Hoegh-Guldberg & Bruno 2010). Regime shifts occur when dominant populations of an ecological community respond gradually and continuously to changes in environmental conditions until a particular threshold or 'tipping point' is reached, beyond which the community rapidly shifts to a new dominant species or suite of species (Scheffer et al. 2001, 2009, Scheffer & Carpenter 2003). In many instances, these 'replacement' assemblages are less 'desirable' from a human standpoint, such as when coral reefs are replaced by fast-growing macroalgae (e.g., Dudgeon et al. 2010) due to a combination of stressors, such as nutrient pollution, overharvesting of herbivorous fishes, disease, and thermal stress (Hoegh-Guldberg et al. 2007, Dudgeon et al. 2010, Hughes et al. 2010). Regime shifts thus have significant implications for ecosystem functioning and services, with consequences for associated ecological, economic, and human social systems (Mumby et al. 2011b). Systems that are already degraded and depleted by non-climatic stressors often have lower resilience and are therefore more susceptible to climate-related regime shifts and tipping points (Folke et al. 2004). Tipping points can be difficult to predict because physiological and ecological thresholds, and significant declines in ecosystem services, can theoretically be reached prior to any associated large-scale changes in the environment (Harley & Paine 2009, Monaco & Helmuth 2011, Mumby et al. 2011b).

Certain US marine systems are on a trajectory for rapid change, and others have already crossed a tipping point (Hoegh-Guldberg & Bruno 2010). In the Chesapeake Bay, eelgrass (*Zostera marina*) died out almost completely during the record hot summers of 2005 and 2010, evidently because too many days exceeded the species' tolerance threshold of 30°C (Moore & Jarvis 2008). Gardner et al. (2003) reported an 80% reduction in Caribbean coral cover, from 50% cover to only 10% cover, in less than three decades. In the northern California Current LME, severe low-oxygen (hypoxic) events have recently emerged as a novel phenomenon due to changes in the timing and duration of coastal upwelling (Barth et al. 2007, Chan et al. 2008). These events have led to high mortality of benthic invertebrates such as Dungeness crabs (Grantham et al. 2004), as well as the loss of rockfish from low-oxygen areas (Chan et al. 2008), with consequences for local fisheries. In many instances, it is unknown whether reversing these rapid, climate-related trajectories of ocean disruption and decline will be possible. However, evidence indicates that reducing non-climatic stressors, such as overharvesting and pollution, can potentially prevent tipping points from occurring (Hsieh et al. 2008, Diaz-Pulido et al. 2009, Sumaila et al. 2011).

One of the most critical approaches to addressing tipping points will be improving the ability to detect and anticipate regime shifts before they occur to enhance preparedness and response efforts. Early-warning signals exist for ecosystems, indicating if a critical threshold is approaching (Scheffer et al. 2009). For example, decreases in the growth, recruitment, and reproduction of key species have been linked to climate-related stress (Philippart et al. 2003, Petes et al. 2008, Beukema et al. 2009). Long-term, integrative observations and monitoring data provide a critical foundation for understanding and documenting early-warning signs of regime shifts (Scheffer et al. 2009), as well as for testing the accuracy of predictive models (e.g., Wethey & Woodin 2008). Enhancing the ability to anticipate tipping points will require integration of long-term observations with experimental and modelling approaches (Scheffer & Carpenter 2003). Advances in determining the underlying physiological and ecological mechanisms responsible for ecosystem regime shifts (Monaco & Helmuth 2011) would help to inform sustainable management of ocean resources under environmental change (Polovina 2005).

Ocean resource managers can no longer expect ‘smooth’ patterns of change, as evidenced by sudden and non-linear regime shifts. Instead, decision makers and managers should expect surprises and work to anticipate and prevent tipping points whenever possible (Lubchenco & Petes 2010). The utility of enhanced understanding and anticipation of tipping points will depend on the ability of management to respond rapidly and effectively (Biggs et al. 2009). Ocean management must include consideration of multiple interacting stressors (Crain et al. 2008), as well as various life-history stages (Runge et al. 2010). Although climate change consistently ranks as a top pressure to marine ecosystems, at global (Halpern et al. 2008a) and regional areas within the United States (e.g., California Current: Halpern et al. 2009b; north-western Hawaiian Islands: Selkoe et al. 2008, 2009), many other stressors play significant roles in impacting overall condition. The potential for the appearance of tipping points in ocean ecosystems lends urgency to minimizing stressors over which there is more direct control at the local scale (e.g., overfishing, nutrient pollution) to enhance resiliency to climate change and ocean acidification (Hsieh et al. 2008, Lubchenco & Petes 2010, Kelly et al. 2011).

Impacts of climate change on human uses of the ocean and ocean services

US marine ecosystems are highly valuable and provide a wide variety of resources and services that support a diverse array of activities, businesses, communities and economies across the nation. Commercial and recreational fisheries in the United States represent an annual multibillion dollar industry (National Marine Fisheries Service [NOAA Fisheries] 2010). Subsistence fishing, defined as fishing for direct consumption or barter without the product entering a market, also contributes significantly to the health and well-being of fishing-dependent communities and local economies across the United States. Most of the effects of climate change on US fisheries will stem from the changes to the fish stocks brought about by direct and indirect climate impacts on productivity and distribution; others stem from impacts that climate has on the fisheries themselves, as well as fishing-dependent communities across the country.

Although not well documented across all marine regions of the United States, evidence to date suggests that substantial socioeconomic impacts to marine resource-dependent communities and economies worldwide are likely. Moving forward, an interdisciplinary perspective will be crucial for analyzing the interwoven impacts of climate change on the socioeconomic uses of marine resources. That said, data are available regarding the extent of human uses of marine resources, as well as the biophysical effects of climate change on marine resources on which those uses depend. There are many potential consequences of climate change on human uses of oceans, such as possible displacement of fishing fleets from their traditional fishing grounds, increased access to polar region environments for navigation and mineral exploration, and changes in the growth and distribution of waterborne pathogens.

The biophysical impacts of climate change on oceans also affect humans and human systems that interact with the ocean. For example, fishing-dependent communities and the national economy are affected by climate-related impacts on populations of marine resources. Understanding climate impacts to fish and shellfish stocks enables improved assessment of the impacts of those changes on fishing behaviours, industries, infrastructure, and communities.

The term *ocean services* refers both to the quantifiable monetary and non-market value that use of the ocean provides and to the currently unquantifiable but identifiable benefits that the ocean provides to humans. The US Commission on Ocean Policy (USCOP) characterized the value of the ocean sector to the United States in the following way:

> The ocean economy, the portion of the economy that relies directly on ocean attributes … in 2000 … contributed more than $117 billion to American prosperity and supported well over two million jobs. Roughly three quarters of the jobs and half the economic value were produced by ocean-related tourism and recreation. For comparison, ocean-related employment was almost 1½ times larger than agricultural employment in 2000, and total economic output was 2½ times larger than that of the farm sector. (USCOP 2004, p. 31; Figure 10)

The report also noted that, to date, the current governmental standards used to measure ocean economy are insufficient because they do not take into account "the intangible values associated with healthy ecosystems, including clean water, safe seafood, healthy habitats, and desirable living and recreational environments" (USCOP 2004, p. 31). Without a greater understanding of these intrinsic values, Americans are dramatically underestimating the value of the oceans and coasts.

Substantial socioeconomic effects in specific areas, some positive and some negative, are likely to result from changes in marine resources due to climate change. Identifying the crucial areas and potential directions of socioeconomic effects is of vital importance. This review discusses three approaches to exploring the impacts of climate change on human uses of the ocean. The first approach is to combine a baseline of current human uses of marine resources with case studies of currently documentable changes occurring in specific marine resources and their associated socioeconomic impacts. The second approach is construction of generally expected impacts given certain changes in specific marine resources and environments. Finally, the implications of all of these changes for marine resource governance systems will be explored.

Climate effects on capture fisheries

Commercial and recreational fisheries in the United States represent an annual multibillion-dollar industry (Tables 1 and 2). Subsistence fishing also contributes significantly to the health and well-being of fishing-dependent communities and local economies across the United States. In the United States, fisheries managed by the federal government are generally defined as fishing activities that take place between 3 and 200 nautical miles from the coastline. Nationwide NOAA

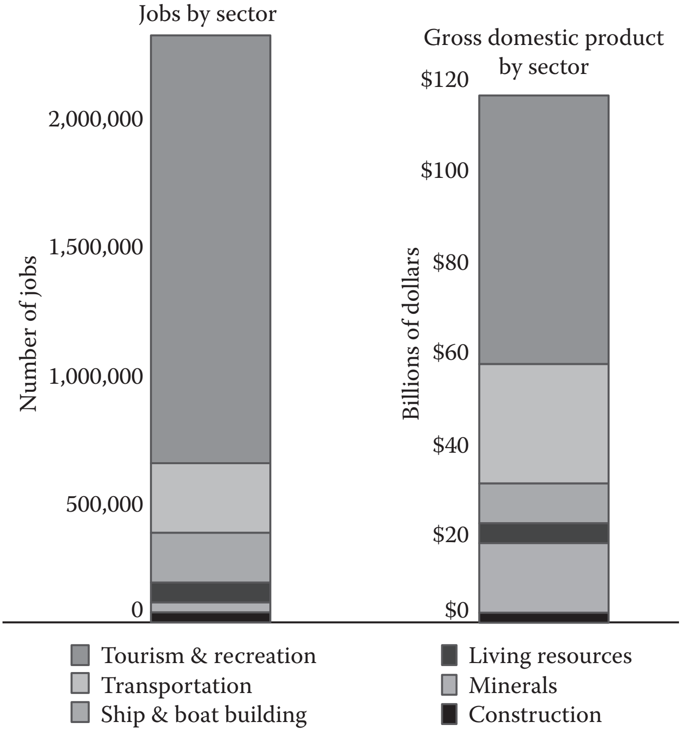


Figure 10 Job numbers and gross domestic product attributable to ocean resources. The ocean economy includes activities that rely directly on ocean attributes or that take place on or under the ocean. On the left, ocean economy is broken down by number of jobs. On the right, ocean economy is broken down by industries' contribution to the gross domestic product in 2000. In 2000, the tourism and recreation sector was the largest in the ocean economy, providing approximately 1.6 million jobs. (Modified from US Commission on Ocean Policy [USCOP] 2004.)

Table 1 2009 Economic impacts of the United States seafood industry

		Jobs	Sales ($1,000s)	Income ($1,000s)	Value Added ($1,000s)
Total Impacts		1,029,542	116,224,548	31,556,643	48,282,319
	Commercial harvesters	135,466	10,349,446	3,435,027	5,340,116
	Seafood processors and dealers	183,895	25,240,441	7,965,719	11,073,240
	Importers	178,387	49,070,476	7,864,480	14,958,830
	Seafood wholesalers and distributors	47,405	6,505,383	2,137,714	3,058,777
	Retail	484,389	25,058,802	10,153,704	13,851,356

Source: National Marine Fisheries Service. 2010. Fisheries Economics of the United States, 2009. US Dept. Commerce, NOAA Tech. Memo. NMFS-F/SPO-118, 172 p.

Fisheries, the primary federal entity with authority over US fisheries management, oversees the management of 230 major fish stocks or stock complexes that comprise 90% of the nation's commercial harvest. In addition, individual US states retain management authority over fishing activities within 3 (or in some cases up to 9) nautical miles of their coasts or in their inland waters, such as Puget Sound (Washington) or Chesapeake Bay (Maryland).

Table 2 2009 Economic impacts of recreational fishing expenditures

		Jobs	Sales ($1,000s)	Income ($1,000s)	Value Added ($1,000s)
Total Impacts		327,123	49,811,961	14,574,464	23,196,422
	For hire	17,217	1,915,452	606,983	1,039,705
	Private boat	31,176	4,243,541	1,253,804	2,158,414
	Shore	35,293	4,312,850	1,319,865	2,243,036
	Durable equipment	243,438	39,340,118	11,393,812	17,755,268

Source: National Marine Fisheries Service. 2010. Fisheries Economics of the United States, 2009. US Dept. Commerce, NOAA Tech. Memo. NMFS-F/SPO-118, 172p.

Changes in the ocean's physical, chemical, and biological processes due to climate change potentially will have an impact on human community reliance on fisheries resources as well as fisheries governance systems. Most of these effects will stem from changes to the fish stocks brought about by direct and indirect climate impacts on stock productivity and distribution; others will stem from impacts that climate has on the fisheries themselves, as well as on fishing-dependent communities. Extreme weather events may also disrupt fishing operations and land-based infrastructure, and sea-level rise may have an impact on both fisheries infrastructure and fishing-dependent communities. However, because the management of fisheries in the United States is partly based on metrics that depend on productivity, such as maximum sustainable yield (MSY), the effects of climate change on fisheries will substantially depend on how fisheries managers respond to those changes.

Alterations in the biophysical characteristics of fish stocks can sometimes mean changing gear (which is often expensive) or learning new fishing grounds and species' habits. Fishers often rely on social networks for information sharing while fishing (e.g., Palmer 1990, Kitts et al. 2007, St. Martin & Hall-Arber 2008, Holland et al. 2010); thus, changing species may result in the need to cultivate new networks. Species whose range extends further north or south may result in fishers making longer trips or relocating their home base, either of which has effects on families and communities. Conversely, commercially important fish that extend their range into new habitat could be beneficial to fishers in the new location. Fishers often choose day versus trip fishing based on family considerations (Maurstad 2000). Where trips are longer, household dynamics change, affecting time with spouse and children and ability to participate in community and school events. Where households relocate, family as well as fishers' social networks are lost, and part of a community's economic base disappears (though the communities where the fishers move gain). Gentrification is creating pressure on small fishing-dependent communities (Clay & Olson 2008, NOAA Fisheries 2009), making coastal property less affordable. Any climate change-related loss of fishing households could exacerbate this trend. The exact degree or even direction of any of these economic impacts for commercial fishers depends on which specific climate impacts occur, factors affecting market dynamics at that point in time (Markowski et al. 1999), and choices based on social and cultural factors.

In addition to commercial fishers, recreational and subsistence fishers will likely be affected by the impacts of climate change. Recreational fishers will largely change target species, with unclear economic impacts, as many aspects of the recreational fishing experience are unrelated to specific species (Fedler & Ditton 1994). Subsistence fishers generally fish a wider range of species than those fishing for pure recreation and so would likely be able to adapt, provided enough species remain accessible (Steinback et al. 2007). However, to the extent that multiple species become unavailable, these fishers may experience negative nutritional consequences, especially since they are also more likely to collect non-fin-fish marine resources (Steinback et al. 2009), such as squid, seaweed, kelp

(Ling et al. 2009) or shellfish, the last of which are expected to be impacted by increasing ocean acidification (Cooley & Doney 2009).

Effects on the productivity and location of fish stocks

The most direct potential effects of climate change on fisheries will come through changes in the productivity and location of the fish stocks that are the targets of those fisheries. How climate change effects will ultimately manifest themselves in the fish stocks is uncertain, in part because the complexity of trophic relationships makes predictions difficult (Brander 2010). Thus, determining which individual fisheries are likely to suffer significant adverse effects from climate change and which are likely to benefit is challenging. Fisheries that target stocks adversely affected by climate change may be able to target alternate stocks that benefit from climate change, so the ultimate impacts depend strongly on the capacity of particular fisheries to adapt to changes (Brander 2010). Similarly, fisheries that target fish stocks with evolving spatial locations will experience changes in the required amount of fuel and other fishing inputs, time at sea, and exposure to ice (Mahon 2002, Badjeck et al. 2010), but whether these changes will be detrimental or beneficial depends on exactly how those locations change and the exact prices (social and economic) associated with the adaptation strategies available to fishers, their families, their communities and fisheries-dependent industries.

Economic effects on commercial fisheries and fishing-dependent communities

Climate change can affect the quantity and quality of yields through biophysical impacts, and the magnitude of these impacts will depend on responses to these changes by harvesting and processing sectors. These responses will be reflected in fish and seafood markets through changes in prices and yield values and through changes in the costs of fishing (e.g., fuel prices). Taken together, it is the net value of fish (i.e., sales revenues minus costs) that will determine incomes of fishers and economic value of fish stocks to fishing-dependent communities.

ENSO-induced climate variability on fisheries can serve as a partial proxy for what could happen to individual fisheries as a result of climate change (Sumaila et al. 2011). In general, ENSO events are associated with a warming of sea-surface temperature in the tropical Eastern Pacific. Dalton (2001) used an ENSO event (1981 to 1999) to estimate the impact of climate change on fisheries in Monterey Bay for sablefish (*Anoplopoma fimbria*), albacore tuna (*Thunnus alalunga*), Chinook salmon (*Oncorhynchus tshawytscha*), and market squid (*Loligo opalescens*). These four fisheries were chosen because together they account for approximately 50% of the revenues associated with landings at Monterey Bay ports. Results showed a 60% decrease in active sablefish vessels in Monterey Bay accompanied by a 25% decrease in ex-vessel price (Dalton 2001). The albacore fishery showed temporary increases in active vessels and ex-vessel prices of approximately 20% in response to a major ENSO event. The Chinook fishery showed no change in numbers of vessels but did exhibit a substantial decrease in ex-vessel prices. Application of the same ENSO model for the market squid fishery showed an increase in ex-vessel price, together with a drastic decrease in the number of active vessels. In fact, there were no recorded landings of market squid at Monterey Bay ports during the major 1998 ENSO event, which had a sea-surface temperature anomaly of 1.9°C.

Unlike ocean warming, which has a robust literature on fisheries impacts (Sumaila et al. 2011), relatively few studies have assessed the wider impacts of ocean acidification on fisheries. Moore (2011) explored the economic impact of ocean acidification on US mollusc production and estimated the economic loss to be approximately \$10 million per year (\$0.07 per US household) in 2020 and to increase to almost \$300 million per year (\$1.78 per US household) in 2100. Based on regression results from a study by Ries et al. (2009) for 18 selected species of marine calcifiers, this impact represents a cumulative cost in net present value terms (with discount rate of 5%) of \$734 million. However, ocean acidification impacts are difficult to predict and not all species will be impacted to the same degree. For example, the effect on blue crabs may not be as negative as that estimated for molluscs. Ries et al. (2009) found that blue crab, *Callinectes sapidus*, did not exhibit significant ocean acidification-related effects. However, there is already some evidence that ocean acidification can have an impact on other crab species (Walther et al. 2009, 2010), and that commercially important crab stocks in the North Pacific, for example, are vulnerable. Furthermore, the small set of previous studies on ocean acidification impacts did not differentiate effects on different life-history stages, including early life stages, which may be especially sensitive (Gazeau et al. 2010); it did not apply to animals where demographic factors are a critical feature of population dynamics, which is clearly the case with many, perhaps most, commercially important species.

Recent scientific concern about ocean acidification is turning to discussions of socioeconomic security (NRC 2010b), particularly to the potential negative impacts of ocean acidification on certain commercial fisheries (Cooley & Doney 2009, Cooley et al. 2009). According to a 2010 NRC report, "Ocean acidification may result in substantial losses and redistributions of economic benefits in commercial and recreational fisheries," adding that, "although fisheries make a relatively small contribution to the total economic activity at a national and international level, the impacts at the local and regional level and on particular user groups could be quite important" (NRC 2010b, p. 89).

In addition to the effects of climate change on fish stocks, both fishery operations and fishing-dependent communities are likely to be directly affected. Extreme weather events can disrupt fishing operations and damage the community-based infrastructure, such as landing sites, boats and gear, that supports the fisheries (Jallow et al. 1999, Westlund et al. 2007, Badjeck et al. 2010). Climate change that manifests itself in increased fluctuations in fishery production and income can affect communities through their choice of livelihoods and other social outcomes (Sarch & Allison 2000, Coulthard 2008, Iwasaki et al. 2009, Badjeck et al. 2010).

Fishing-dependent communities in the United States and elsewhere are diverse in economic and social characteristics. The effects of climate change on fisheries may be felt more acutely by those communities that are more dependent on fishing (i.e., those with fewer alternative economic activities or higher reliance on fisheries—especially for subsistence) and those that are more dependent on one or a few fish stocks (i.e., those less diversified in their target fisheries) (Phillips & Morrow 2007).

Overall, it is projected that the impact of climate change and ocean acidification on commercial fisheries will result in decreased job security for workers employed in commercial fishing gear manufacturing and sales, vessel loading, vessel construction and repair, fish and shellfish processing, wholesale and retail, commercial docks, ice suppliers to commercial fishing vessels, and other support industries, possibly resulting in income decline and job loss. Workers in recreational fishing gear and vessel sales, recreational outfitting, marinas, and other recreational support industries could also be affected.

Regional effects of climate change on fisheries

Although the specific effects of climate change on particular marine ecosystems and fish populations are difficult to predict, on a global and regional basis there is sufficient research to indicate that many, but not all, of these impacts will be negative (Grafton 2010). Some fish stocks are experiencing shifting distributions; for others, their overall abundance or population characteristics are fluctuating due to climate-induced shifts in marine ecosystems. The following presents a review of this research regarding the regional effects that are known or expected.

Subsistence fishing and hunting in the North Pacific Alaskan communities and local economies depend on, and are engaged in, subsistence harvesting of marine resources more than any other region in the United States. Regional climatic and environmental changes are already having a notable (though unpredictable and often non-linear) effect on subsistence activities in the ocean environment, through changes in hydrology, seasonality and phenology, and fish and wildlife abundance and distributions (White et al. 2007, Loring & Gerlach 2009, McNeeley 2009, Rattenbury et al.

2009, Loring et al. 2011). Residents of rural Alaska are already reporting unprecedented changes in the geographic distribution and abundance of fish and marine mammals, increases in the frequency and intensity of storm surges in the Bering Sea, changes in the distribution and thickness of sea ice, and increases in coastal erosion. When combined with ongoing social and economic change, changes in climate, weather, and the biophysical system interact in a complex web of feedbacks, making life in rural Alaska extremely challenging.

Climate change-related effects on alterations in sea ice and weather patterns are also already creating numerous new environmental challenges for those who harvest marine species. The most striking change in the Arctic marine environment in recent years has been the rapid loss of summer sea ice (Perovich et al. 2011). In the Bering, Chukchi, and Beaufort Seas off Alaska's coast, this physical change has led to many ecological impacts (Moore & Gill 2011, Mueter et al. 2011b) and altered physical access to the region (AMSA 2009, Arctic Monitoring and Assessment Program [AMAP] 2008), affecting human use of marine resources.

For example, residents of Alaska Native communities rely on sea ice to ease their travel to the hunting grounds for whales, ice seals, walrus and polar bears. Krupnik et al. (2010) identified numerous effects of climate change that challenge and threaten local adaptive strategies, including times and modes of travel for hunting, fishing and foraging. In addition to the stress on marine mammal and polar bear populations, possibly resulting in lower quality and reduced number of prey, hunters will have to travel farther and longer to reach haul-outs and will have to travel over open water for greater distances, both of which will increase the risks associated with hunting for subsistence-dependent populations (Gearheard et al. 2006). Fuel and vessel maintenance costs associated with subsistence hunting will also increase as hunters need to travel greater distances (Callaway et al. 1999).

The impacts of climate change on Alaskans are also seen in shifts in the abundance and distribution of culturally important species. Salmon, which has been described as the cultural keystone food of Alaska, has become a less-dependable subsistence resource than in the past, with direct implications for food security (Loring & Gerlach 2010). A closure of the king salmon fishery on the Yukon River in 2009, for example, resulted in empty storage facilities, empty smokehouses and barren fish racks from Stevens Village to Fort Yukon and beyond. The 2009 closure produced a 'perfect storm' for a food security crisis, especially in combination with low harvest rates of moose and other terrestrial resources in some areas, the high price of fuel, and climate-driven changes in hydrology and water resources (Loring & Gerlach 2010).

Climate change effects on commercial fishing in the North Pacific The Eastern Bering Sea groundfish fishery, from which 14% of the total value of the fisheries of the United States is taken, is conducted north of the Alaskan Peninsula and Aleutian Islands (Hiatt et al. 2010). Climate change-related shifts in atmospheric conditions, ocean properties, and ecosystem interactions have the potential to greatly affect this multibillion-dollar industry. However, little concrete information is available regarding how these fisheries will be affected. Potential climate change impacts on North Pacific fisheries have been studied in only the past few years. Specific studies have examined how Pacific salmon, walleye pollock and Pacific cod populations are expected to react. Salmon populations are expected to be impacted by increased snowmelt and water flows, causing fall/winter floods that could affect salmon eggs laid in gravel beds (Low 2008). In the summer, higher average summer temperatures could diminish the oxygen content of the water in streams where smolts (juvenile fish) live, thus increasing smolt mortality. Warmer temperatures could also affect migration of smolts and lead to timing mismatches with their zooplankton prey base, timing that is critical as they enter salt water. While climate change impacts on fisheries in the North Pacific have not yet been well studied, it is anticipated that they could be significant. Studies have found that while there has been a northwards shift in the distribution of pollock and cod fishing in recent years (2006–2009), the northwards shifts are associated with colder-than-average years in the Bering Sea

(Haynie & Pfeiffer 2012, Pfeiffer & Haynie 2012). A large ice and cold pool extent concentrates fish populations in the northern region of the fishing grounds, giving fishers in the north an advantage over those in the south. The redistribution has occurred in both the winter and summer seasons of the Pacific cod fishery and in the summer pollock fishery. However, there has been little redistribution of effort in the winter pollock fishery, which is driven by the pursuit of valuable roe-bearing fish that spawn in the southern part of the Eastern Bering Sea. This large difference in value per fish in the roe fishery means that harvesters are unlikely to shift to the north for marginal increases in catchability.

Climate change effects on subsistence and commercial fishing on the West Coast For tribes in the US Pacific North-west, questions have been raised recently about how climate change will affect the maintenance and reproduction of indigenous rights for salmon and other marine species whose distributions may change with a changing ocean environment (Colombi 2009). The right to harvest marine resources on traditional fishing grounds is guaranteed to these tribes through government-to-government treaties (NOAA Fisheries 2009). However, allocation of catch is based on allowable catch quantities, and treaty rights to harvest have referred to tribal 'usual-and-accustomed' fishing areas. Since some predictions of climate change impacts involve target species range shifts (Mantua et al. 2010), as water temperatures and prey ranges shift, the implications for geographically bounded tribal fishing rights are uncertain and of great to concern to North-west 'treaty tribes'.

Similarly, non-tribal fishers relying on personal use of marine resources are potentially impacted by changes in the abundance and range habitats of targeted nearshore species, as well as by climate-based shoreline shifts that may disrupt shoreside infrastructure. In Los Angeles County, more than three-quarters of a million low-income adults live with hunger or make daily decisions about whether to eat or pay for other essential needs, such as shelter or clothing (Harrison et al. 2007). To the extent that urban extraction of locally caught seafood represents a coping strategy for such food insecurity, potential nearshore climate change impacts present livelihood and nutritional issues for a number of pier-based fishers.

Little has been documented regarding how climate change is affecting fisheries along the West Coast of the United States. However, the largest effects on fisheries will likely be due to changes in the distributions and the abundance of stocks, as is documented in other regions. Perhaps the best example of known effects of climate variability on fish stocks in the Pacific is with the California sardine fishery; during a warm regime, biomass of Pacific sardine increases, and conversely, a cold-water regime results in a decrease in abundance of the sardine stock. In response to fluctuations in productivity due to climate variability, the US Pacific sardine fishery is managed using an environmentally based harvest control rule to determine the annual harvest level. The harvest control rule is intended to prevent overfishing, sustain consistent yield levels (Herrick et al. 2007), and reduce the exploitation rate if stock biomass decreases or if ocean conditions become cooler and less favourable for the stock. However, given the general lack of existing research and modelling capabilities on socioeconomic impacts of climate change on fisheries, the impacts on Pacific sardine fisheries are uncertain.

Climate change effects on subsistence and commercial fishing in the Pacific Islands Much of the fishing effort in the Pacific Islands region depends on species and habitat associated with coral reefs (Bell et al. 2011). Coral reef habitats, and therefore the fish species that depend on them, are threatened by changes to water temperature, acidification of the ocean, sea-level rise, and possibly more severe cyclones and storms (Bell et al. 2011). The loss of live corals results in local extinctions and a reduced number of reef fish species (Karl et al. 2009). Declining coral reefs will have an impact on coastal communities, tourism, fisheries, and overall marine biodiversity; abundance of commercially important shellfish species may decline, and negative impacts on finfish may occur (Fletcher

2010). Reduced catches of reef-associated fish will widen the expected gap between the availability of fish and the protein needed for food security.

A recent assessment published by the Secretariat of the Pacific Community (SPC) assessed the vulnerability of tropical Pacific fisheries and aquaculture to climate change (Bell et al. 2011). The assessment did not include Hawaii but covered 22 Pacific Island countries and territories. Across the region, fish provide 51–94% of the animal protein in the diet in rural areas and 27–83% in urban areas. The great majority of fish needed for food security in the region is derived from coastal subsistence fishing; in 14 of the countries and territories, 52–91% of the fish eaten in rural areas is caught from coral reefs and other coastal habitats, and high levels of subsistence fishing are common in urban areas on many of the smaller island areas (Pratchett et al. 2011).

Nearly 70% of the world's annual tuna harvest, approximately 3.2 million tons, comes from the Pacific Ocean. Climate change is projected to cause a decline in tuna stocks and an eastwards shift in their location (IPCC 2007). On balance, the Pacific Island countries and territories (including the United States) appear to be in a better position than nations in other regions to cope with the implications of climate change for fisheries and aquaculture. Expected effects for the region as a whole are among the better possible outcomes worldwide. In particular, the Pacific Island commonwealths and territories (PICTs) with the greatest dependence on tuna (e.g., Kiribati, Nauru, Tuvalu and Tokelau) are likely to receive greater benefits as the fish move east, whereas the projected decreases in production occur in those PICTs where industrial fishing and processing make only modest contributions to GDP and government.

However, projections that storms (including cyclones, hurricanes and typhoons) could become progressively more intense would pose increased risk of damage to shore-based facilities and fleets for domestic tuna fishing and processing (Bell et al. 2011), as well as increased risk to safety at sea. The increased costs associated with repairing and relocating shore-based facilities and addressing increased risks to fishers' safety, could affect the profitability of domestic fishing operations. Aquaculture impacts could also occur; for example, changing patterns of precipitation and more intense storms could damage aquaculture ponds or make small pond farming more difficult due to more frequent droughts (Bell et al. 2011). There could also be higher financial risks associated with coastal aquaculture as a result of greater damage to infrastructure from rising sea levels and more severe storms.

For island fisheries sustained by healthy marine ecosystems and coral reefs, climate change impacts could exacerbate stresses such as overfishing, affecting both fisheries and tourism that depend on abundant and diverse reef fish (Karl et al. 2009). This context suggests that how society responds and adapts to the impacts of climate change not only may reduce some effects but also could exacerbate others, especially in the short term. One approach to addressing climate change impacts to subsistence fisheries is to reduce other types of fishing (i.e., commercial and recreational). Another likely response to reducing climate change effects on coral reefs and associated fish species will be the establishment of marine protected area (MPA) networks (Mumby et al. 2011a), which can enhance the resilience of marine resources to climate change and could protect certain areas from additional fishing pressure. When climate change poses risks to protected species such as monk seals (Baker et al. 2006) or loggerhead turtles (Van Houtan & Halley 2011), the resulting measures could potentially include reduced access to fisheries.

Climate change effects on fisheries in the South-east Given limitations on the current knowledge of the biophysical effects of climate change in the south-eastern region, little is known about how the ocean services provided by the South Atlantic and Gulf of Mexico are or will be impacted. However, one of the most pronounced effects of climate change in the Gulf of Mexico is likely to be the increased intensity of hurricanes, whose impacts already include the loss of wetlands and barrier islands that protect or serve as nursery grounds for marine resources. The Gulf Coast represents the region with the highest potential for annual hurricane seasons that disrupt all types of fishing

Table 3 Known or expected direction of social and economic impacts on some major north-eastern commercial and recreational species

Species	Direction of impact
Atlantic cod (*Gadus morhua*)	Negative
Atlantic croaker (*Micropogonias undulatus*)	Positive
Atlantic lobster (*Homarus americanus*)	Ambiguous, but perhaps more negative
Atlantic sea scallop (*Placopecten magellanicus*)	Negative
Blue crab (*Callinectes sapidus*)	Negative

Source: Based on Hare et al. 2010; Fogarty et al. 2008; Frumhoff et al. 2007.

(NOAA Fisheries 2009). Loss of coastal habitat along the Gulf Coast has been well documented (Ingles & McIlvaine-Newsad 2007), and barrier island and wetland losses are projected to increase in the future. In addition, with the possible increases in hurricane intensity, storm surge and high winds, communities that rely on coastal marine resources for subsistence are likely to be increasingly limited in their ability to undertake harvesting activities.

Climate change effects on subsistence and commercial fishing in the North-east For North-east fishers and the families, households, firms and communities that depend on them, the most relevant changes are those occurring to the ocean of the North-east US shelf ecosystem (NEUS) and its denizens. Water temperatures are rising, surface seawater pH is decreasing, precipitation is increasing, salinities are decreasing, and stratification is increasing (EAP 2012). All of these changes have an impact on marine life (Table 3).

Some North-east species, such as Atlantic cod (*Gadus morhua*), will likely move into Canadian waters and out of the range of North-east fishers due to warming water temperatures (Fogarty et al. 2008). Others, such as Atlantic croaker (*Micropogonias undulatus*), will likely see an increase in biomass as well as a range shift northwards from the Mid-Atlantic into southern New England, thus providing New England fishers with a larger stock to fish on but leaving Mid-Atlantic fishers with less easy access (Hare & Able 2007, Hare et al. 2010). Yet other species, such as American lobster, will likely also see their ranges move northwards, leaving the waters of New York and Rhode Island and increasing their presence in Maine; however, warmer waters may also lead to increases in 'lobster shell disease' (Frumhoff et al. 2007), making the impact on fishers more difficult to judge. Increased acidity could affect shellfish, including scallops, lobsters, and blue crab—three of the North-east's highest-value species, so economic and social impacts are potentially high (Cooley & Doney 2009, McCay et al. 2011). Certain shellfish (e.g., lobster) could also suffer from sea-level rise if the coastal wetlands necessary to their juvenile stages are flooded (Frumhoff et al. 2007).

However, marine ecological changes are not the only climate change issues affecting fishers and fishing-dependent industries. Sea-level rise will also flood coastal infrastructure, especially docks and other fishing-related structures that are on the very edge of the current coastline. In the North-east, many smaller ports have already lost infrastructure to gentrification (Gale 1991, Colburn & Jepson 2012), among other causes. With vital infrastructure such as boat repair facilities concentrated in fewer ports, loss in any of the remaining hubs could have important negative impacts on the entire region's fishing fleet (NOAA 1997a,b, Robinson & Gloucester Community Panel 2003, Robinson et al. 2005).

Implications of climate change for aquaculture

The United States imports 86% of its seafood, and approximately half of that is from aquaculture production. Two-thirds of marine aquaculture is molluscan shellfish, such as oysters, clams, and mussels, and the remainder is shrimp and salmon, with lesser amounts of barramundi, sea bass, sea bream, and other species. The impacts of climate change on global aquaculture are not yet fully known. Unlike capture fisheries, organisms being reared in captivity are subject to more controlled environments that may allow for acclimation or adaptation. Captive breeding can also lead to reduction in genetic heterogeneity, which can make populations even more vulnerable to stress (given lower diversity/resilience).

As in commercial, recreational and subsistence capture fisheries, climate impacts of aquaculture are likely to be both positive and negative, arising from direct (e.g., through physical and physiological processes) and indirect impacts (e.g., through impacts on the natural resources required for aquaculture), the major issues being water, land, seed, feed and energy (De Silva & Soto 2009).

Direct impacts of climate change on aquaculture

A rise in sea-surface temperatures may trigger the growth of HABs that can extend the spatial or temporal scope of a bloom or release toxins into the water and kill cultured fish and shellfish, particularly for fish in cage-based aquaculture systems and shellfish beds. Higher water temperatures may also result in increased disease incidence and parasites, which may develop more rapidly in warmer waters and higher salinities and threaten the aquaculture sector. Species cultured in temperate regions, predominantly salmon and cod species, have a relatively narrow range of optimal temperatures for growth. For example, temperatures over 17°C would be detrimental to the salmon-farming sector due to heat stress, causing feed intake to drop and feed utilization to be reduced (De Silva & Soto 2009).

Certain aspects of aquaculture may benefit from climate-related changes. Higher water temperatures may also increase the availability of new culture sites, especially in areas previously too cold to support aquaculture. An increase in water temperature may also have a positive effect on metabolism and stimulate growth of cultured species, as long as the change is gradual and within the thermal tolerance range of the species.

Aquaculture does have some advantages for dealing with climate-related impacts. The tool of selective breeding could potentially give aquacultured stocks an adaptive advantage since changes in preferred genetic traits can be as high as 10% per generation for selective breeding programmes (Gjøen & Bentsen 1997). Most aquacultured species still contain a great deal of genetic diversity, which means they should be adaptable to the direct impacts of climate change. Likewise, aquacultured organisms can be treated for parasites and diseases (Moffitt et al. 1998, DIPNET 2007). Vaccination, selective breeding, and better nutrition have all improved the resistance of farmed fish to wild diseases, and this trend is likely to continue (Torrissen et al. 2011).

Indirect impacts of climate change on aquaculture

The dependence of aquaculture on fishmeal and fish oil becomes an important issue under most climate change scenarios (De Silva & Soto 2009). Tacon et al. (2011) estimated on a global basis that in 2008 the aquaculture sector consumed 3.72 million metric tons of fishmeal (60.8% of the total global fishmeal production) and 0.78 million metric tons of fish oil (73.8% of the total reported global fish oil production in 2008). Industrial fishmeal and fish oil production is typically based on a few, fast-growing, short-lived, productive stocks of small pelagic fish in the subtropical and temperate regions. The major stocks that contribute to this global industry, of which the United States is a major exporter, are the Peruvian anchovy, capelin, sandeels, and sardines.

Schmittner (2005) has predicted that the biological productivity of the North Atlantic will decrease by 50% and ocean productivity worldwide by 20% due to climate change. Changes in productivity would greatly impact the availability of the small pelagics for fishmeal and oil. It is also possible that predicted changes in ocean circulation patterns will result in the occurrence of ENSO influences becoming more frequent, with impacts on the reliability of stocks of the small pelagics utilized for fishmeal and fish oil production.

Ocean acidification and aquaculture

In North America, ocean acidification is currently considered a serious near-term threat because of its potential to alter ocean food webs in a relatively short time period (De Silva & Soto 2009). For aquaculture, ocean acidification particularly influences shell formation and affects filter-feeding shellfish. Protecting vulnerable marine organisms grown in aquaculture facilities from the effects of ocean acidification may be possible in theory, but it presents practical challenges. Aquaculture is often conducted on land in tanks or ponds that are filled with coastal seawater or within coastal ocean pens. Adjusting seawater chemistry before supplying culture tanks on land would require equipment and monitoring that might increase the overhead of aquaculture operations, and aquacultured animals in nearshore operations cannot be shielded from ocean acidification (Cooley & Doney 2009).

Social impacts of climate change on aquaculture

Impacts of climate change on capture fisheries, such as damage to physical capital and impacts on transportation and marketing systems and channels, are likely to be mirrored in aquaculture (Cochrane et al. 2009). Likely the greatest social impact of climate change that must be dealt with by the aquaculture industry is on human health. Seafood consumption may have a number of health benefits, including improved cardiovascular function, reduced inflammatory disease, reduced macular degeneration, reduced mental depression, and higher IQ (Institute of Medicine 2006, FAO/WHO 2011). It is also clear that aquaculture will be necessary to supply the increased volume of seafood needed to support a growing global population. If climate change reduces wild harvest, then the production from aquaculture will have to be that much greater to meet the demand.

Offshore energy development

Oil and gas

Offshore oil and gas development has been increasing in recent years. The oil and gas industry and its consumers now face having to adapt to climate changes that they contributed to generating. Industry reaction will vary by type (international companies, small independents, or state owned); specific geographic location; local policies and regulations; the company's ethics; and combined industry performance on the national and international markets. Figure 11 illustrates the perspective of adaptive government regulations in Alaska, which have been changing with warmer temperatures (Arctic Climate Impact Assessment [ACIA] 2004). These issues need to be analyzed and understood in a broad context, given that the oil and gas industry not only delivers oil and gas, but also provides jobs.

The impacts of climate change on the marine sector of the oil and gas industry can be direct (e.g., on-site changes of environmental conditions) or indirect (e.g., pressures exerted by the public and governments). The financial impact of climate policies and restricted access to reserves, due to environmental protections or because companies are developing resources in less-accessible locations every year, is estimated to reduce shareholder value by between 1% and 7%, depending on the company (Austin & Sauer 2002).

Impact factors Currently, five primary impacts of climate change have been associated with recent offshore oil and gas exploration (Acclimatise 2009a):

1. *Increased Pressure on Water Resources*: Changing rainfall amounts, the need for potable water, and droughts will all increase the demand for water, which is key in sustaining oil and gas production.

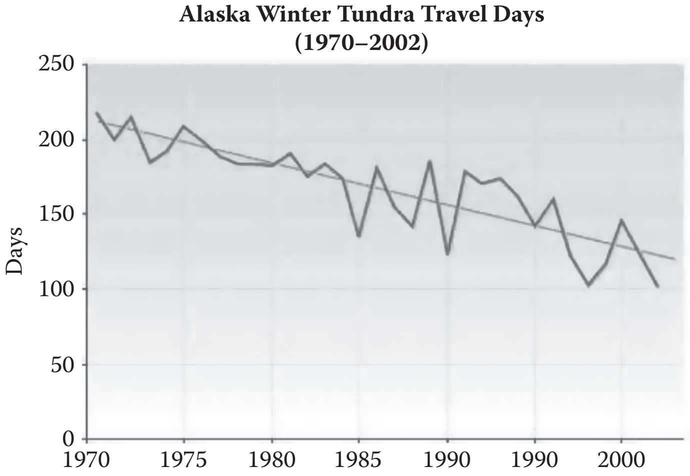


Figure 11 Adaptive government regulations in Alaska for oil exploration. The number of days in which oil exploration activities on the tundra are allowed under the Alaska Department of Natural Resources standards halved from 1970 to 2002 due to permafrost thaw, which is disrupting transportation, damaging buildings and assets (and in particular pipelines) and increasing the risk of pollution. Operational costs are increasing for oil and gas companies. (From Arctic Climate Impact Assessment [ACIA] 2004.)

2. *Physical Asset Failure*: Several types of existing equipment not only are old but also were designed to function under climate conditions typical of 20 to 40 years ago. Included in this category are energy supplies (e.g., generators and batteries), off-site utilities, and waste and water treatment technologies.
3. *Employee Health and Safety Risks*: As environmental conditions change, the oil and gas industry is exploring potential oil and gas reserves in areas (e.g., ultradeep waters, the Arctic Ocean) where ambient conditions are significantly more extreme and dangerous for industry workers than areas under current use, with consequent increases in insurance costs, salaries and other operational costs.
4. *Drop in Value of Financial Assets*: To meet the growing demand for energy, oil and gas companies need to continue securing investments for new exploration, production and manufacturing. Potential investors and stakeholders are placing greater importance on the business impacts of climate change as the risks have an impact on cost and revenue drivers. Beyond the safety-driven increases noted, insurance costs could potentially rise because of greater risk of physical plant damage due to extreme weather events.
5. *Damage to Corporate Reputation*: As knowledge and awareness of climate change grows, any failure to monitor and report the impacts of climate change on social and ecological resources is increasingly likely to harm oil and gas companies' reputations. Contractual relationships that do not adequately foresee and manage risks driven by climate change may damage a company's reputation with stakeholders, increasing the risk of parties turning to litigation.

Changes in regulations Governments will variably have an impact on the oil and gas industry based on their particular climate change policies and regulations. Fish and marine mammal species foreign to the Arctic Ocean just 5 years ago are starting to be sighted for the first time off the northern shore of Alaska (Acclimatise 2009b). These new inhabitants of the Chukchi and Beaufort Seas will likely trigger new protective measures by state and federal regulatory agencies.

At lower latitudes, in the Gulf of Mexico area, it is likely that future tropical weather events (such as typhoons and hurricanes) will become more intense (Ulbrich et al. 2008). However, these modelling projections carry uncertainties, thus making it difficult to anticipate the magnitude of such changes in the development of new regulations. It may be that industry is already responding to potential changes in the regulatory environment. For example, in 2006, following the extreme 2005 hurricane season, the American Petroleum Institute launched a process for reviewing design and safety standards for offshore oil platforms. Additional regulations will certainly increase operational costs; however, these risks will also be accompanied by opportunities. Reduced sea ice coverage, for instance, will lead to the opening of new shipping lanes, facilitating the transport of crude oil between the Atlantic and the Pacific Oceans. New or amended regulatory regimes may thus be required for these areas.

Drivers for change and projections New regulations will require companies to invest in alternatives to fossil fuels and develop cleaner and more sustainable energy sources. It is hoped those changes will be reflected by an increase in profits in the mid- and long terms. There is consensus that the adoption of carbon sequestration procedures, combined with the inclusion of renewable energy production, will transform the current oil and gas industry (Lovell 2010). This new version will have the capacity to deliver energy products obtained from both renewable and non-renewable sources, simultaneously reducing emissions as required for compliance with national and international regulations.

The future of the industry The great dilemma that society and oil and gas companies face today is based on balancing growing requirements to limit greenhouse gas emissions with desires for increased energy consumption and company profits (Van den Hove et al. 2002). Different companies have taken different approaches to this dilemma (Van den Hove et al. 2002). For instance, some companies argue that the risk of climate change is less than the risk of negative impacts to a profitable oil and gas industry that can boost the economy and technological development since reduced profits would presumably impact the entire economy (Button 1992, Van den Hove et al. 2002). Other companies weigh this question of profits and the well-being of the economy versus climate change impacts on society and ultimately the economy as well, providing their own weights and justifications. It is also possible that some or all of these companies might focus on lowering emissions, especially if they are convinced that this approach will maximize profits.

Renewable energy (wind, ocean waves and currents)

While coastal and marine environments do not currently host commercial facilities that generate electricity, several projects are proposed, and pilot projects are being tested. The possible types of renewable energy that may be developed in coastal and marine environments include wind, wave, ocean current, tidal, hydrogen generation and solar. The Bureau of Ocean Energy Management (BOEM, then the Minerals Management Service) prepared a Programmatic Environmental Impact Statement (PEIS) (BOEM 2007) which examined the potential environmental consequences of alternative energy development. The PEIS analysis determined that wind, wave and ocean current technologies were the most advanced and likely to be developed on the outer continental shelf. Along the Atlantic Coast, one wind facility is approved for development, and several others are proposed. Wave energy is most intense along the Pacific Coast, and technology testing is under way. The Gulf Stream along the south-eastern coast of Florida is the most favourable for ocean current development, and one pilot project is in development.

With respect to climate impacts, coastal and marine renewable energy projects are evaluated as mitigation measures because they do not directly result in emissions of greenhouse gases. The effects of climate change on the renewable energy industry have not been assessed, either along the US coast or elsewhere. However, as with the oil and gas industries, climate change is expected to affect the industry. Potential impacts include damage to infrastructure from increased storm intensity through larger waves, stronger currents, or sediment erosion and potential change in the resource being harnessed, including changes in wind speed, wave height, or ocean current intensity or direction. These changes could have either a positive or negative effect.

The offshore renewable energy sector is nascent and, unlike the financially self-sustaining oil and gas industry, requires investment from the public sector, at least in the United States, as construction of offshore facilities is more costly; specifically, offshore wind is more expensive than onshore. Uncertainty based on climate change projections could alter the evaluation of risk and potentially deter speculative investments in this emerging industry.

Tourism and recreation

Tourism is an important part of the US economy, contributing \$1.8 trillion in economic output and supporting 14.1 million jobs in 2011 (US Travel Association 2012). Tourism is also one of the few sectors that has been growing during the current tentative economic recovery, with 101 million international tourist arrivals to North America in 2011, up 2.9% from 2010 (United Nations World Tourism Organization [UNWTO] 2012). Nationally, 2.8% of gross domestic product, 7.52 million jobs and \$1.11 trillion in travel and tourism total sales are supported by tourism (Office of Travel and Tourism Industries [OTTI] 2011a,b).

Coastal tourism and recreation are used to describe all tourism, leisure, and recreationally oriented activities that take place on the coast and in coastal waters. Main activities involved in coastal tourism and recreation include visiting beaches, diving and snorkelling, cruises, boating and sailing, and bird and marine mammal watching. In addition, infrastructure, such as hotels, restaurants, vacation homes, marinas, dive shops, harbours and beaches, are present in coastal areas to support these tourism and recreational activities. Tourism statistics are difficult to disaggregate solely for coastal areas; however, the most recent data from the OTTI show that in 2009–2010, nine of the top ten states and US territories visited by overseas travellers were coastal (including the Great Lakes), and seven of the top ten cities were located on the coast (OTTI 2011a,b). An estimated 1.5 billion person-trips for leisure, based on overnight trips in paid accommodations or travel to destinations 50 or more miles from home, occurred in the United States in 2010 (US Travel Association 2012).

In the face of climate change, impacts to marine resource distribution, variable weather conditions, and extreme events such as typhoons and hurricanes are expected to pose the most significant impacts on the tourism industry. However, the projected impacts of climate change are expected to affect tourism and recreation industries and their associated infrastructure in a variety of ways: positively, negatively and mixed (Scott et al. 2004, Moreno & Becken 2009, Yu et al. 2009). Unfortunately, the science of assessing predicted impacts on these industries is still in its early stages.

Many coastal and marine tourism and recreational activities depend on favourable weather and climate. Activities such as diving and snorkelling rely on comfortable water and air temperatures and calm waters for boat travel to snorkelling and dive sites. Weather-related impacts, such as potential changes in wind patterns and wave height and direction, could affect activities such as sailing and surfing. Temperature is predicted to have an impact on biophysical events, such as marine mammal and seabird migrations, affecting recreation involving watching or interacting with these animals (Lambert et al. 2010). Arctic cruise tourism is expected to increase with increasing sea-surface temperatures and decreased sea ice during Northern Hemisphere summers (Stewart et al. 2007). However, researchers warn that climatic warming in the Arctic may change the distribution of sea ice, resulting in negative implications for tourist transits in the High Arctic and North-west Passage regions (Stewart et al. 2007).

Sea-level rise may also have an impact on coastal tourism and recreation in a variety of ways. Increased sea levels are likely to reduce the size of sandy beaches in some areas and possibly increase erosion rates (Yu et al. 2009). Hawai'i's Waikiki Beach is recognized as a major tourism destination and a popular recreational spot for both visitors and residents. In 2007, approximately 4 million tourists visited Waikiki Beach, and hotels sold 3.9 million room nights (State of Hawai'i Department of Business, Economic Development and Tourism [DBEDT] 2008). Given the popularity and economic importance of Waikiki, the issue of beach erosion has been an ongoing concern. It is estimated that nearly $2 billion in overall visitor expenditures could be lost per year due to complete erosion. Also, an estimated $66 million in tax revenue would be lost. Indirect effects could include hotel industry job loss of over 6000 jobs per year. In addition, higher sea levels could cause the landwards migration or flooding of coastal lagoons and other coastal habitats for species, such as seabirds, that are attractive for wildlife viewing (Bird 1994). Furthermore, sea-level rise threatens coastal infrastructure, such as marinas, boardwalks, hotels and houses, both directly and indirectly with increased inundation and erosion (Scott et al. 2004).

Finally, HAB events have been shown to significantly reduce reported business revenues for the lodging and restaurant sectors in affected coastal communities, with implications for local and state tax revenues (Hoagland et al. 2002). Morgan et al. (2010) estimated how and why participation in marine-based activities (e.g., beach-going, fishing, and coastal restaurant patronage) were affected during a red tide event. The authors found that recreational activities of 63% and 70% of south-western Florida residents who go saltwater fishing or go to beaches, respectively, were adversely affected (cancelling, delaying, cutting short their trip, or relocating their trip) by red tide events during the previous year. Given that the geographic and temporal scale of red tides have been shown to be affected by water temperature and potentially water quality, it is likely that climate change could increase their occurrence.

Human health

In addition to current and future climate change impacts on the biophysical and socioeconomic aspects of marine resources, there is a broader growth in knowledge of the human health dimensions of global climate change. Public health scientists with the US National Center for Environmental Health at the Centers for Disease Control and Prevention (CDC) have identified a number of primary areas in which climate change has an impact on human health and will likely exacerbate human vulnerability and sensitivity in the future (McGeehin 2007). These include, but are not limited to, extreme weather-related injuries, morbidity and mortality; decline in access to drinkable water; increased food insecurity and malnutrition; rising pollutant-related respiratory problems; and increased spread of infectious disease. This list of consequences illustrates the complex and varied ways in which the social impact of climate change in the United States extends beyond actuarial statistics and measures of economic loss and includes broad, critical aspects of human health, well-being and vulnerability (Brown 1999).

Health and vulnerability

Complex social and ecosystem conditions inform the reach and range of climate change effects on health, which is "not some absolute state of being but an elastic concept that must be evaluated in a larger socio-cultural context" (Baer et al. 2003, p. 5). While the environmental health effects of climate change on marine resource users in particular are not widely known, there is growing recognition of human vulnerability and sensitivity in the wake of global climate change. Vulnerability is a fundamental concept for assessing the role of climate change in determining health, especially because it merges theory and empirical findings from disaster studies in general and public health science, social and economic analysis and risk assessment in particular (Baer & Singer 2009). Disease vulnerability and environmental health risk may both become increasingly central issues in research exploring connections among climate change, marine resource contamination or decline, and poverty, especially since subjugated populations in coastal regions tend to be marine resource users.

Waterborne and foodborne diseases

The impact of warming oceans on waterborne pathogens that cause both seafood-related and direct contact wound infections has generated growing concern in a time of climate change. Much attention has been directed at pathogens in the *Vibrio* family, especially *V. cholera*, in global health research and intervention (Lipp et al. 2002). More recently, with regard to US cases, there has been increased concern about other *Vibrio* species, including *V. parahaemolyticus* and *V. vulnificus*, both known sources of seafood-related acute gastroenteritis. In 2011, the CDC, which maintains a voluntary surveillance system of culture-confirmed *Vibrio* infections in the Gulf of Mexico region, estimated 45,000 annual cases of *V. parahaemolyticus* and 207 cases of *V. vulnificus* in the United States (CDC 2011, Hlavsa et al. 2011). The highest concentrations of *Vibrio* infections were in the Mid-Atlantic states that surround Chesapeake Bay, where 305 cases were reported in 2009. Given this high concentration in Chesapeake Bay, there is a high likelihood that these numbers could increase significantly if water temperatures in the bay rise in the future.

There has been reported expansion of *V. parahaemolyticus* in the Pacific North-west and Alaska that closely corresponds with climate anomalies related to El Niño (CDC 1998, McLaughlin et al. 2005, Martinez-Urtaza et al. 2010). In addition, in the days after Hurricane Katrina, 22 *Vibrio* wound infections were recorded, of which 3 were caused by *V. parahaemolyticus*, 2 of which led to the deaths of the infected individuals (CDC 2005).

Vibrio vulnificus is perhaps the most threatening pathogenic *Vibrio* in the United States because of its highly invasive nature and high fatality rate following infection (Horseman & Surani 2011). In recent years, it has come to be recognized as the most virulent foodborne pathogen in the United States, with a fatality rate as high as 60% (Oliver 2005), and has been responsible for the overwhelming majority of reported US seafood-related deaths (Oliver & Kaper 2007). *V. vulnificus* can be transmitted to humans by way of consumption and dermal exposure. The bacterium is frequently isolated from oysters and other shellfish in warm coastal waters during the summer months. Since it is naturally found in warm marine waters, people with open wounds can be exposed to *V. vulnificus* through direct contact with seawater. A review of this bacterium found the death rate among domestically acquired foodborne illness associated with *V. vulnificus* (34.8%) was significantly higher than any of the other 31 foodborne pathogens assessed (ranging from 0 to 17.3%) (Scallan et al. 2011). In addition, *V. vulnificus* is becoming a significant and growing source of potentially fatal wound infections associated with recreational swimming, fishing-related cuts, and seafood handling (Weis et al. 2011). One study reported that almost 70% of infected individuals developed secondary lesions requiring tissue debridement or limb amputation (Oliver 1989). *V. vulnificus* is most frequently found in water with a temperature above 20°C, which is especially important given the significant changes in temperature that are anticipated in coastal waters over the coming decades. While there is no definitive link between the increasing incidence of *Vibrio* and climate change, sufficient data, such as these, are available to warrant closer research attention (Greer et al. 2008).

In addition to members of the *Vibrio* family, a number of other marine pathogens merit monitoring in a warming environment. *Aeromonas hydrophila* is a widely distributed inhabitant of both fresh and salt waters, as well as a common fish pathogen. In humans, it is known to cause gastroenteritis and a variety of extraintestinal infections, including endocarditis, pneumonia, conjunctivitis, and urinary tract infections, and is also capable of causing localized wound infections in individuals with intact immune systems (Collier 2002). *Myobacterium marinum* infections, of which approximately 200 are reported each year in the United States, have been described as an emerging necrotizing mycobacteria-caused disease involving both marine and freshwater exposure during a water-related injury (Dobos et al. 1999). *Erysipelothrix rhusiopathiae* is found in diverse animal species, including fish and shellfish. Successfully transferred to humans through cuts, this pathogen causes cutaneous eruptions on the hands or fingers. It is popularly referred to as 'shrimp picker's disease' and 'crab poisoning' in marine locations (Brooke & Riley 1999). Increased rates of infection have been documented for these emerging diseases. Like *V. vulnificus*, each of these pathogens has the potential for increased rates of infection as a result of warming ocean waters.

Harmful algal blooms and climate change

HABs, which occur worldwide and in all US states, have recently increased in duration and geographic range and have also involved new species and impacts (Moore et al. 2008, Hallegraeff 2010, Anderson 2012). Many HABs produce potent toxins that can kill or sicken humans, fish, birds, turtles, marine mammals, domestic animals and pets. Human health is threatened through exposure to toxin-contaminated shellfish and fish, drinking water, or aerosols. Monitoring and adaptations, such as shellfish harvesting closures, beach closures, and drinking water treatment minimize threats to human health. Control measures, while critical to protect public health, can reduce the availability of important sources of nutrition or income to communities that depend on the impacted resources. The economic consequence, based on a subset of HAB events that affected the United States, has been conservatively estimated at $82 million per year (Hoagland & Scatasta 2006), but only some of the impacts listed are included in this estimate.

HAB occurrence may be altered by climate change impacts, including increases in water temperature, stratification, and increased CO_2; alteration of currents or hydrology; and changes in nutrient availability due to upwelling or run-off. However, HABs are caused by a diverse group of organisms, and their growth and toxicity will respond very differently to changing environmental conditions. Increases in cyanobacterial blooms (CyanoHABs), many of which produce cyanotoxins linked to liver, digestive, skin, and neurological illness and even death, have already been well documented and attributed to a combination of increased nutrients and climate change (Paerl & Paul 2012). Massive toxic blooms threaten drinking water supplies and recreational use of water bodies, especially in areas experiencing droughts. For other HABs, change in climate may increase the period of time when environmental conditions are suitable for blooms to occur. For example, in Puget Sound (Washington State), as in many areas in the north-western and north-eastern United States, shellfish harvesting is often closed for a period in the late spring or summer. The closure period corresponds to the window of opportunity when environmental conditions are optimal for blooms of *Alexandrium* (Moore et al. 2008, 2009). This toxic dinoflagellate produces potent neurotoxins that can cause illness and death in humans when they eat contaminated shellfish. Climate change scenarios indicate that the window of opportunity will increase substantially, even for modest climate change projections (Moore et al. 2011).

Climate change may also alter conditions so that they become unfavourable for HAB growth. Ciguatera fish poisoning (CFP) is caused by ciguatoxin produced by a benthic dinoflagellate, *Gambierdiscus*, living on macroalgae on tropical hard substrates, especially coral reefs. The toxins accumulate in higher trophic level fish, which, when consumed by humans, causes CFP, a debilitating illness. CFP is the most common HAB-caused illness in the world, and it also deters fish consumption in many areas where protein is in short supply. A recent study (Tester et al. 2010) showed that CFP incidence in the Caribbean is highest where water temperatures are highest and postulated that climate change may be one factor in recent outbreaks of CFP from fish caught near oil platforms in the more temperate Gulf of Mexico (Villareal et al. 2007). However, data from the South Pacific suggest that waters may become too hot for the causative organism to grow (Llewellyn 2010); therefore, it is possible that the geographic distribution of CFP may change, but not the incidence.

Health risks related to climate impacts on marine zoonotic diseases

A global analysis of trends in infectious diseases found that emerging infectious disease events were increasing over time and were dominated by zoonotic diseases (transmitted between animals and humans), with the majority of those diseases (72%) originating in wildlife (Jones et al. 2008). Climate change may have an impact on infectious zoonotic diseases by prolonging periods when diseases may be transmissible and by changing geographic ranges of disease and animal reservoirs (Greer et al. 2008).

It has been difficult to make a definitive link between increases in marine zoonotic disease and climate change due to multiple contributing stressors (Wilcox & Gubler 2005, Burek et al. 2008), as well as lack of sufficient baseline data for some organisms (Burek et al. 2008), but there are examples of changes in latitudinal distributions of infectious organisms. For example, *Lacazia loboi* is a cutaneous fungus that has been reported to infect humans and dolphins in tropical and transitional tropical climates. The disease more recently has been diagnosed in dolphins off the coast of North Carolina, which represents a change in the latitudinal distribution of this fungus (Rotstein et al. 2009). To detect such changes, it is critical to continue monitoring and conducting assessments of disease in marine animals to establish baselines and identify trends. Furthermore, an integrated monitoring and surveillance system will be important to provide early warnings and better public information for any emerging diseases that are a threat to human health. Some coastal and tribal communities that depend on marine animals as traditional sources of nutrition are particularly vulnerable to outbreaks that have an impact on their already at risk food supply.

Health risks of extreme weather events

People living in coastal environments might also be at greater health risk when considering the increases in extreme weather events resulting from global climate change (Greenough et al. 2001). The IPCC noted that warming would vary by region but would overall be accompanied by changes in precipitation, in the variability of climate, and in the frequency and intensity of some extreme weather phenomena (IPCC 2007). The health risks of extreme weather are many, including, but not limited to, injury from storm wreckage, risks associated with poor drainage and impaired sanitation, heat exhaustion and other heat-related illnesses (Semenza et al. 1999, McGeehin & Mirabelli 2001, Bernard & McGeehin 2004, Luber & McGeehin 2008), mental health illnesses (CDC 2006, Norris et al. 2006, van Griensven et al. 2006), and vector-borne and zoonotic diseases (Parmenter et al. 1999, Glass et al. 2000, Enscore et al. 2002, Collinge et al. 2005, Eisen et al. 2007, Gage et al. 2008).

Globalized seafood and emerging health risks

Due to a rise in both the globalization of seafood and demand in the US market, the Food and Drug Administration (FDA) reports that the United States now imports more than 80% of its seafood supply, including wild-caught fish and aquaculture fish (US Food and Drug Administration [USDA] 2008). This seafood originates from over 13,000 suppliers in over 160 countries, with China being the largest exporter of seafood to the United States by volume (US Government Accountability Office [GAO] 2004). Imported seafood can be a source of health risk involving multiple agents, especially bacteria (e.g., *Salmonella*, *Campylobacter*, verotoxin-producing *Escherichia coli*, *Listeria*); parasites (*Toxoplasma gondii*, *Cyclospora cayetanensis*, *Trichinella*); and viruses (norovirus, hepatitis A virus), as well as rarer infectious agents and mycotoxins (Buisson et al. 2008). The critical question is whether climate change and the further globalization of seafood will contribute to additional increases in the prevalence of infected seafood available to consumers in the American market.

Climate change has the potential to adversely impact imported seafood in two ways. First, climate change is a risk to the degree that warming oceans and other changes in the marine environment increase rates of infection of various seafood stocks worldwide (including locations that export seafood to the United States). Second, rising temperatures and changing weather patterns may result in inadequate cooling of seafood at various points in the import process, allowing the growth of infectious agents. These scenarios, combined with the relatively low level of FDA testing of imported seafood, suggest the need for increased attention to this potential threat to US public health in a time of climate change.

Governance challenges

Many natural resource governance institutions have been built assuming stable environmental conditions that are similar to observed historical experience (Peloso 2010). In many instances of greater climate variability or climate change, these assumptions will be challenged or no longer valid. Climate change impacts on the distribution and accessibility of living natural resources and ecosystems will in some cases require changes in jurisdictional boundaries established by national or international management institutions. While governments can employ technologies to achieve better climate change preparedness and response, it is important to keep in mind that "technologies are only as effective as the social and political networks that use them for risk assessment, planning and responding to disasters" (Dowty & Allen 2011). In this regard, the National Academy of Sciences has repeatedly called for early, active, continuous, and transparent 'community' involvement in risk management decisions, and not just reliance on technology-based decisions (NRC 1996, 2000a,b) orchestrated by government scientists and experts (Fischer 2000). This broader, more inclusive governance approach is ever more important as marine resource users and coastal communities (1) increasingly adapt and respond to changing security conditions, the restructuring of transportation networks, and a warming climate; and (2) demand further involvement in climate change discussions, especially those resulting in changes in marine resource management decisions and policies.

Fisheries management in the United States

Federal fisheries management occurs mainly within the framework of the Magnuson-Stevens Fishery Conservation and Management Act (MSA). Within this framework, eight fishery management councils develop fishing regulations for specific regions and fisheries in cooperation with the US federal government, represented by the National Marine Fisheries Service. Management plans from the councils are designed to meet 10 national standards set by the MSA. Important among these standards is the requirement to prevent overfishing while achieving optimum yield. This optimum yield is the basis for caps on total harvest or annual catch limits (ACLs). ACLs are established by the Scientific and Statistical Committees (SSCs) of the Fishery Management Councils. The SSCs often establish uncertainty buffers to prevent overfishing. The SSCs are able to adjust annual harvest recommendations to fluctuations in stock size to prevent overfishing. For example, there is evidence that warming trends in the Bering Sea have caused increased overlap of pollock and salmon stocks, which has led to increased salmon by-catch rates in the pollock fishery (Stram & Evans 2009). As a result, the North Pacific Fishery Management Council (NPFMC) has taken steps to minimize salmon by-catch rates by limiting pollock fishing at certain times and in certain areas.

Climate change has an impact on stock levels, spatial distribution, and year-to-year variability in stock levels, resulting in increased uncertainty that can have an impact on decisions made by fisheries management, such as total allowable catch (TAC) limits and ACLs. For example, the survey area on which a stock assessment is based may no longer appropriately cover the range of the species, perhaps leading to an assessment suggesting a stock decline as opposed to a shift in location. This could result in setting a TAC lower than it should be for a stock that is otherwise healthy, costing fishers their livelihood. Uncertainties, such as accurate stock range, are likely to be built into the setting of more conservative TACs and ACLs. Changes in marine target populations mean managers must anticipate problems and build flexibility into management plans; many current regulations tie fishers to particular species in specific areas (Organization for Economic Cooperation and Development [OECD] 2010). Further, significant discussion needs to take place on societal value of fish stocks and those communities that depend on fishing to sustain their livelihoods. Transboundary and other jurisdictional issues will also emerge (Herrick et al. 2007).

Governance challenges associated with transboundary stocks are likely to increase, given that international agreements on fishing shared stocks are based on stable, historical abundance and spatial distribution patterns. Miller and Munro (2003) used a theoretical model to illustrate potential problems with transboundary Pacific salmon stocks in the United States and Canada. Their results highlight the need to update existing, or in some cases negotiate new, more flexible, international agreements. To adequately account for, and ultimately reduce, the amount of uncertainty related to climate change, enhanced monitoring and improved stock assessment methodology are needed.

Offshore energy development

Climate change will present new opportunities and new challenges to offshore energy development. New areas, especially in the Arctic, will become accessible to development and to marine energy transport, but this will also bring industry activities into contact and potential conflict with new environments and other uses, such as subsistence and tourism. Operations in new and traditional areas may face new climactic challenges with increasing storms, more severe operating conditions and more sensitive species and ecosystems. In addition, routine operations, such as oil transport, are likely to carry increased risk in Arctic waters, where lack of charts, extreme weather conditions and poor oil spill response capability hamper safe operations. Additional regulations will certainly increase operational costs, although in the Arctic, these risks will also be accompanied by opportunities as the reduced sea-ice coverage will lead to the opening of new shipping lanes, facilitating the transport of crude oil between the Atlantic and the Pacific Oceans. There is potential for restructuring of both current fisheries and offshore energy policy and management regimes through approaches such as the creation of protected areas for various marine resources and habitats.

Tourism and recreation

Tourism is seldom recognized as a single sector for policy and regulation. Policies in many different sectors, such as shipping (cruise ships), fisheries management (marine sanctuaries and protected areas), habitat protection (regulation of coastal development), and the business sector (departments and chambers of commerce), affect tourism and the tourism industry. As such, changes made by the governance structures in each of these sectors in response to climate change are likely to have an impact on tourism and recreation in the United States. An important consideration is the safety of life at sea, as with decreasing summer sea ice, tourists and cruise vessels venture into higher latitudes and uncharted waters far from established ports and rescue capabilities. The International Maritime Organization and the Arctic Council are already cooperating to increase governance measures in this area.

Human health

The consequences of climate change related to human health showcase the complex and variegated ways in which the social impact of climate change in the United States extends beyond measures of economic loss to broader and very critical aspects of human health, well-being, and vulnerability (Brown 1999). There are a large number of agencies in each country at the international, national, state and local levels that develop policy and regulations for these areas, including seafood safety, water quality, disaster response and disease outbreak avoidance and containment and that will need to develop adaptive means to respond to these changes.

International implications of climate change

Climate change and marine ecosystems neither begin nor end at the US border. Many marine organisms, such as fish, marine mammals, and seabirds, are highly migratory and do not remain in one jurisdictional boundary. As climate change increases, certain species will likely shift their ranges, expanding into countries where they were previously absent. Current protected area networks may not match critical sites needed in the future. The focus of much conservation work has historically been on critically endangered species. It is crucial that in light of climate change, attention is also given to ensuring that other species and populations remain robust and resilient to the changes that are projected to occur throughout the marine biome (Simmonds & Eliott 2009).

Multilateral regional fisheries management organizations (RFMOs) of which the US is a member are aware of the issue of climate change. Flexible management strategies will be needed that will allow these organizations to manage fisheries sustainably. Only half of the 12 RFMOs that include US fish species have taken or are taking actions to address climate change (Table 4). In addition, none of the six existing bilateral fisheries agreements between the United States and neighbouring countries have formally addressed climate change issues. Bilateral fishing regimes, which tend to be renegotiated periodically, will have to evolve over time in response to climate-related changes in abundance and spatial and temporal changes in fish stocks. The fishery governance process is much slower to adapt for an RFMO, for which the process is built on a stable decision environment (convention or treaty) and existing environmental conditions.

Security and transportation issues are at play in terms of expected climate change impacts to ocean services in the United States. Most notably, climate shifts in the Arctic (especially decreases in sea-ice coverage) are provoking discussion on the future of ocean governance, including marine resource and ecosystem-based management. Perhaps the most noteworthy issue in this arena is the increase in shipping accessibility in the Arctic. National security concerns and threats to national sovereignty have also been a recent focus of attention (Campbell et al. 2007, Borgerson 2008, Lackenbauer 2011). Ocean change will lead to an expanded geopolitical discussion involving the relationships among politics, territory, and state sovereignty on local, national, and international scales (Nuttall & Callaghan 2000).

International forums that deal with species conservation have a major role in providing coordination and direction. Therefore, international collaboration is both fundamental and foundational to understanding and managing climate change in the United States. Strengthening existing international partnerships, and developing new partnerships for knowledge sharing and strategy development, will be necessary to understand and address climate change impacts on marine ecosystems and communities around the world. Working closely with partner countries to enhance the level of understanding of climate change impacts is needed to build capacity and to effectively plan and implement adaptation actions.

Implications of climate change in international conventions and treaties

A number of international treaties and conventions have been developed to aid in addressing ocean issues that affect multiple jurisdictions and countries. Many of these either focus primarily on marine resources or involve them in some fashion. Exploring and strengthening synergies between these treaties and conventions would provide increased value, better coordination, improved focus and facilitation of the development of key priorities (Robinson et al. 2005). The following discussion includes only a subset of the larger body of international conventions and treaties that are considering climate change.

Convention on Migratory Species

The Convention on Migratory Species (CMS) of Wild Animals is the only global intergovernmental convention that is established exclusively for the conservation and management of migratory species (Robinson et al. 2005). The CMS recognizes that nations have a duty to protect migratory species that live within or pass through their jurisdictional boundaries, and if effective management of these species is to occur, concerted actions will be required from all nations (range states) in which a species spends any part of its life cycle (Robinson et al. 2005). Species are listed under two CMS appendices: Those species threatened with extinction are listed in Appendix I, and species that would benefit from internationally coordinated efforts are listed in Appendix II. The

Table 4 Primary regional fisheries management organizations (RFMOs) and arrangements that include US living marine resources, by organization/membership, mission, relevant species, and climate change actions, 2012

Organization/US membership status	Mission	Relevant species	Climate change actions
Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR)/ member	Protect and conserve the marine living resources in the waters surrounding Antarctica	Fish, molluscs, crustaceans and all other species of living organisms, including birds	CCAMLR includes climate change on the agenda of its Scientific Committee, which reports on this item to the commission. Climate is also a factor considered in the development of a proposal for a marine protected area in the Ross Sea.
North Atlantic Salmon Conservation Organization (NASCO)/ member	Promote scientific research and the conservation, restoration, enhancement, and rational management of salmon stocks in the North Atlantic Ocean	Atlantic salmon (*Salmo salar*)	NASCO is concerned about the potential impacts of climate change on wild Atlantic salmon and requested the International Council for the Exploration of the Sea (ICES), which provides scientific advice to the organization, to advise it on the potential implications of climate change for salmon management at the 29th NASCO Annual Meeting held in Edinburgh, Scotland, on 5–8 June, 2012. NASCO has not published any studies directly addressing climate change and salmon to date.
North Pacific Anadromous Fish Commission (NPAFC)/ member	Promote the conservation of anadromous stocks and ecologically related species in the high-seas areas of the North Pacific Ocean	Pacific salmon (chum, coho, pink, sockeye, chinook, cherry, and steelhead)	The Bering-Aleutian Salmon International Survey-II (BASIS-II) is NPAFC's coordinated program of cooperative research on Pacific salmon in the Bering Sea designed to clarify the mechanisms of biological response by salmon to the conditions caused by climate change. Climate change and its impact on salmon have been discussed in a symposium and two special publications: (1) a report on understanding impacts of future climate and ocean changes on the population dynamics of Pacific salmon (Beamish et al. 2009) and (2) a bibliography of literature associated with climate and ocean change impacts on Pacific salmon (Beamish et al. 2010). The overarching theme of the NPAFC 2011–2015 Science Plan is "Forecast of Pacific Salmon Production in the Ocean Ecosystems Under Changing Climate."
Northwest Atlantic Fisheries Organization (NAFO)/member	Study, conserve and manage fishery resources in the NAFO Regulatory Area in the North Atlantic Ocean beyond 200-mile zones of member states	Cod, flounders, redfish, capelin, hake, skates, shrimp	The NAFO Scientific Council Standing Committee on Fisheries Environment has been discussing change patterns, including climate change, for nearly 50 years. Beginning in 1964, NAFO conducted four symposia on decadal reviews (1950–1959, 1960–1969, 1970–1979, 1980s–1990s) of environmental conditions in the North-West Atlantic and their influence on fish stocks.

continued

Table 4 (continued) Primary regional fisheries management organizations (RFMOs) and arrangements that include US living marine resources, by organization/membership, mission, relevant species, and climate change actions, 2012

Organization/US membership status	Mission	Relevant species	Climate change actions
Western and Central Pacific Fisheries Commission (WCPFC)/ member	Ensure, through effective management, the long-term conservation and sustainable use of highly migratory fish stocks in the western and central Pacific Ocean in accordance with the 1982 U.N. Convention on the Law of the Sea and the 1995 U.N. Fish Stocks Agreement	All fish stocks of the species listed in Annex 1 of the 1982 Convention on the Law of the Sea occurring in the convention area and such other species of fish as the commission may determine	There is a growing awareness in the WCPFC Science Committee that the impact of oceanographic and climate variability is a key area of uncertainty, and that it should be integrated in future stock assessments (Commission for the Conservation and Management of Highly Migratory Fish Stocks in the Western and Central Pacific Ocean. Summary Report of the Seventh Regular Session of the Scientific Committee, 21 September 2011).
Western Central Atlantic Fishery Commission (WECAFC)/ member	Promote the effective conservation, management and development of the living marine resources of the area of competence of the commission and address common problems of fisheries management and development faced by members of the commission	All living marine resources, without prejudice to the management responsibilities and authority of other competent fisheries and other living marine resources management organizations or arrangements in the area	At the 13th session of the commission in 2008, parties addressed an agenda item titled "Climate Change Implications for Fisheries and Aquaculture: Contributions to Global Discussion From FAO." Parties agreed that there was a need for improved coordination and collaboration between countries in the region in improving disaster preparedness. In particular, there was a need to improve the collation and distribution of available information on climate change and its likely impacts. Fishers have said that little information is reaching them on climate change in relation to small-scale fisheries. Advance warning also needs to be improved in the region. Parties concluded that implementation of an ecosystem approach to fisheries management was an important mechanism for maximizing the resilience of marine ecosystems to climate change. The fifth session of WECAFC's Scientific Advisory Group recommended that the commission pay attention and provide appropriate response to the impact of climate change and climate variability on marine ecosystems, fishing communities and fisheries and aquaculture in general (WECAFC/XIV/2012/4).

United States is a range state for many of the marine species listed in these appendices, including whales, seabirds, turtles, and sharks (Table 5).

Cooperation between countries to tackle the impacts of climate change on specific migratory species is critical for effective management. The CMS provides an important opportunity to develop climate change strategies at the international level. A number of climate change actions have already been undertaken by CMS. One such action was an effort led by the Zoological Society of London to develop and test a climate change vulnerability assessment method for the United Nations Environmental Program CMS Secretariat on approximately half of the Appendix I species.

Table 5 Marine species with US ranges listed in the Convention on Migratory Species Appendices

Appendix	Taxa	Species
I	Mammals	Humpback whale (*Megaptera novaeangliae*), bowhead whale (*Balaena mysticetus*), blue whale (*Balaenoptera musculus*), northern Atlantic right whale (*Eubalaena glacialis*), North Pacific right whale (*Eubalaena japonica*)
I	Birds	Short-tailed albatross (*Phoebastria albatrus*), Bermuda petrel (*Pterodroma cahow*), Hawaiian petrel (*Pterodroma sandwichensis*), pink-footed shearwater (*Puffinus creatopus*)
I/II	Mammals	Sperm whale (*Physeter macrocephalus*), sei whale (*Balaenoptera borealis*), fin whale (*Balaenoptera physalus*), West Indian manatee (*Trichechus nanatus*)
I/II	Birds	Steller's eider (*Polysticta stelleri*)
I/II	Reptiles	Green turtle (*Chelonia mydas*), loggerhead turtle (*Caretta caretta*), hawksbill turtle (*Eretmochelys imbricata*), Kemp's Ridley turtle (*Lepidochelys kempii*), olive Ridley turtle (*Lepidochelys olivacea*), leatherback turtle (*Dermochelys coriacea*)
I/II	Fish	Basking shark (*Cetorhinus maximus*), great white shark (*Carcharodon carcharias*), manta ray (*Manta birostris*)
II	Mammals	Narwhal (*Monodon monoceros*), pantropical spotted dolphin (*Stenella attenuata*), spinner dolphin (*Stenella longirostris*), striped dolphin (*Stenella coeruleoalba*), killer whale (*Orcinus orca*), Baird's beaked whale (*Berardius bairdii*), Beluga whale (*Delphinapterus leucas*), northern bottlenose whale (*Hyperoodon ampullatus*), Bryde's whale (*Balaenoptera edeni*), dugong (*Dugong dugong*)
II	Birds	Black-footed albatross (*Phoebastria nigripes*), laysan albatross (*Phoebastria immutabilis*), black-browed albatross (*Thalassarche melanophris*), shy albatross (*Thalassarche cauta*), Salvin's albatross (*Thalassarche salvini*), white-chinned petrel (*Procellaria aequinoctialis*), spectacled petrel (*Procellaria conspicillata*), roseate tern (*Sterna dougallii*), Arctic tern (*Sterna paradisaea*), little tern (*Sterna albifrons*)
I/II	Fish	Whale shark (*Rhincodon typus*), shortfin mako shark (*Isurus oxyrinchus*), longfin mako shark (*Isurus paucus*), porbeagle (*Lamna nasus*), spiny dogfish (*Squalus acanthias*), green sturgeon (*Acipenser medirostris*)

Of these, approximately 50% are marine species. Results indicated that all of these species will be negatively impacted by climate change, including many species with ranges in the United States (Table 6). Continuing this work in a more quantitative way is considered a key priority for the future.

A technical workshop held in June 2011 included experts from academia, non-governmental organizations (NGOs), intergovernmental organizations (IGOs) and government agencies that work on issues associated with migratory species and climate change (CMS 2011). This workshop helped to charter a way forward and recommended key areas for future action and focus, including

- Predicting how future range shifts should be considered;
- Establishing long-term datasets and baselines of species listed under CMS, as well as their critical prey items;
- Developing historical and shifting baseline maps illustrating threats at spatiotemporal scales and zoning maps for use in planning of renewable energy projects;
- Focusing on populations that are resilient and adaptive to climate change;
- Integrating ecological networks into the design of protected areas;
- Highlighting that mitigation of climate change can be potentially more harmful to migratory species if sites are not carefully selected (e.g., wind farms may cause high mortality to bird and bat populations without proper siting and precautions);
- Recognizing that tertiary effects, such as new shipping routes in the Arctic, are increasing disturbance and exploitation of marine migrants, and biodiversity-related multilateral environmental agreements may be beneficial to coordinate responses;

Table 6 Marine species under the Convention on Migratory Species with US ranges that are vulnerable to climate change

Vulnerability	Taxa	Species
High	Reptiles	Green turtle (*Chelonia mydas*), hawksbill turtle (*Eretmochelys imbricata*), Kemp's Ridley turtle (*Lepidochelys kempii*), loggerhead turtle (*Caretta caretta*), olive Ridley turtle (*Lepidochelys olivacea*), leatherback turtle (*Dermochelys coriacea*)
High	Mammals	North Pacific right whale (*Eubalaena japonica*), Northern Atlantic right whale (*Eubalaena glacialis*), bowhead whale (*Balaena mysticetus*), blue whale (*Balaenoptera musculus*), narwhal (*Monodon monoceros*)
High	Birds	Short-tailed albatross (*Phoebastria albatrus*), Bermuda petrel (*Pterodroma cahow*), Steller's eider (*Polysticta stelleri*)
Medium	Mammals	Sperm whale (*Physeter macrocephalus*), sei whale (*Balaenoptera borealis*), humpback whale (*Megaptera novaeangliae*)
Medium	Fish	Basking shark (*Cetorhinus maximus*), great white shark (*Carcharodon carcharias*)

- Continuing to address research needs related to emerging issues such as disease, invasive species and ecosystem changes;
- Building capacity at the local level through climate change literacy training, participatory monitoring and creating incentives among communities for conservation; and
- Integrating climate change policies into additional multilateral agreements and strengthening collaboration with the Convention on Biological Diversity (CBD), Ramsar, the Bern Convention and United Nations Framework Convention on Climate Change (UNFCCC).

There is a need for multinational large-scale and long-term work to better understand risks associated with ocean and marine resources as a result of climate change. Focus must be given to ensuring that species and populations, in addition to those that are critically endangered, are able to combat the effects of climate change predicted to occur throughout the marine biome (Simmonds & Eliott 2009).

Convention on wetlands of international importance (Ramsar)

The United States is a contracting party to Ramsar, which is an intergovernmental treaty that provides the framework for voluntary national action and international cooperation for the conservation and wise use of wetlands and their resources. Parties of Ramsar

> work towards the wise use of all their wetlands through national land-use planning, appropriate policies and legislation, management actions, and public education … and ensure their effective management; and cooperate internationally concerning transboundary wetlands, shared wetland systems, shared species, and development projects that may affect wetlands. (http://www.ramsar.org)

There are nearly 2000 designated Ramsar sites around the world, over 30 of which are in the United States.

Many marine and coastal wetlands identified by Ramsar are particularly important habitats for ocean and marine species and include, among others, permanent shallow marine waters (e.g., sea bays and straits); marine subtidal aquatic beds, which include kelp beds, seagrass beds, tropical marine meadows; coral reefs; and rocky marine shores (e.g., rocky offshore islands, sea cliffs). The Ramsar Convention, similar to CMS, has explicitly recognized the threats caused by climate change and plays an important role in the future by understanding that additional work is required in understanding the relationship between wetlands and climate changes.

Convention on International Trade in Endangered Species of Wild Fauna and Flora

The United States is a party to the Convention on International Trade in Endangered Species (CITES) of Wild Fauna and Flora, which regulates the trade in species based on their conservation status. Appendix I species are those threatened with extinction and are, or may be, affected by trade. Parties are not allowed to trade in Appendix I species for commercial purposes. Appendix II species are not necessarily threatened with extinction but might be if trade is not regulated, and parties may trade in these species as long as trade is not detrimental to their survival. Appendix III species are listed unilaterally by parties seeking international cooperation in controlling trade.

Recently, CITES has begun to focus attention on the issue of climate change. In 2010, the scientific aspects of the provisions of CITES and the resolutions of the conference of the parties were assessed to determine which provisions were actually or likely to be affected by climate change and to make recommendations for further action. A working group was created to draft recommendations to be presented at the 62nd Standing Committee meeting in July 2012. The working group was tasked with addressing climate change in six CITES processes or mechanisms: species listing, non-detriment findings, periodic review of the appendices, management of nationally established export quotas, review of significant trade, and trade in alien invasive species. It was the general consensus that the decision-making framework developed within CITES is flexible enough to accommodate the consideration of climate change in each of its six processes or mechanisms.

Inter-American Convention for the protection and conservation of sea turtles

The Inter-American Convention (IAC) is focused on marine turtles, which are particularly vulnerable to climate change. It promotes the protection, conservation and recovery of the populations of marine turtles and those habitats on which they depend on the basis of the best-available data and taking into consideration the environmental, socioeconomic and cultural characteristics of the parties (Article II, Text of the Convention). These actions should cover both nesting beaches and the parties' territorial waters. International collaboration is essential to marine turtle conservation because turtles that breed on US beaches (or migrate through US waters) need continued protection once they leave US jurisdiction. IAC is an intergovernmental treaty that provides the legal framework for countries in the Western Hemisphere to take actions for the benefit of these species. Continued active involvement of the United States in international expert groups and initiatives provides key support to emerging collective adaptation action for marine turtles.

In 2009, the parties agreed to a number of actions specifically to address the impacts of climate change on marine turtles, including management actions as well as research and monitoring (http://www.iacseaturtle.org). According to annual reports submitted by the parties, overall performance against these goals has been fair; however, climate adaptation concerns are often overtaken by more immediate priorities, such as by-catch and non-climate impacts on nesting beaches.

Convention on Biological Diversity

Climate change is likely to become one of the most significant drivers of biodiversity loss by the end of the century (Millennium Ecosystem Assessment [MEA] 2005). Conserving and restoring marine ecosystems (including their genetic and species diversity) is essential for the overall goals of both the CBD and the UNFCCC. The objectives of the CBD are 3-fold: (1) the conservation of biological diversity, (2) the sustainable use of its components, and (3) the fair and equitable sharing of the benefits arising from the utilization of genetic resources. The CBD affirms that conservation of biodiversity is a common concern of humankind and reaffirms that nations have sovereign rights over their own biological resources. The convention covers both terrestrial and marine biota, and parties are explicitly required to implement the CBD consistent with the rights and obligations of states under the United Nations Convention on the Law of the Sea (UNCLOS). The convention was opened for signature at the United Nations Convention on Environment and Development in Rio de Janeiro, June 1992, and entered into force on 29 December 1993. The United States has signed the convention but has not yet ratified it.

The CBD Conference of the Parties has made over 40 decisions regarding biodiversity and climate change since the convention entered into force. Among those decisions, perhaps the most promising was adopted at the 10th meeting of the CBD in Nagoya, Japan, in 2010, which urged parties to "enhance the conservation, sustainable use and restoration of marine and coastal habitats that are vulnerable to the effects of climate change or which contribute to climate-change mitigation, such as mangroves, peatlands, tidal salt marshes, kelp forests and seagrass beds" (CBD 2010 COP 10 Decision X/33). The decision not only reaffirmed the importance of these habitats and the need to protect them but also played a role in achieving the objectives of the UNFCCC, the Ramsar Convention on Wetlands, and the CBD.

Climate change considerations in other international organizations

Agreement for the Conservation of Albatross and Petrels

The Agreement for the Conservation of Albatross and Petrels (ACAP) is an international multilateral agreement that seeks to reduce known threats to albatrosses and petrels through coordinating international activity. Twenty-two species of albatrosses and seven species of petrels are currently listed under ACAP. Since 2008, the ACAP Advisory Committee has had a standing agenda item "Impacts of Global Climate Change". Recently, ACAP parties have acknowledged that there is growing scientific evidence that present climate change is already affecting marine ecosystems at all levels of the food webs, and projection of future change suggests that these effects will increase considerably. For this reason, the parties recognized that it is important to review the potential impact of global climate variability and change on the conservation status of albatrosses and petrels. However, published studies to date are limited to a few species in the Indian Ocean. Therefore, the committee has recommended that parties and range states encourage further analyses on the combined impacts of environmental change and fisheries on albatross and petrel population trends.

International Whaling Commission

The International Whaling Commission (IWC) is the body charged with the proper conservation of the world's whale stocks, thus making possible the orderly development of the whaling industry. The main duty of the IWC is to review and revise as necessary the measures laid down in the Schedule to the Convention, which govern the conduct of whaling throughout the world. These measures, among other things, provide for the complete protection of certain species; designate specified areas as whale sanctuaries; set limits on the numbers and size of whales that may be taken; proscribe open and closed seasons and areas for whaling; and prohibit the capture of suckling calves and female whales accompanied by calves. The compilation of catch reports and other statistical and biological records is also required.

Climate change and its impacts on cetacean species have been highlighted in discussions at the IWC Scientific Committee, which has considerable expertise in understanding and modelling climate impacts. The IWC passed a resolution requesting contracting governments to incorporate climate change considerations into existing conservation and management plans, directing the Scientific Committee to continue its work on studies of climate change and the impacts of other environmental changes on cetaceans, as appropriate, and appealed to all contracting governments to take urgent action to reduce the rate and extent of climate change. The IWC has also hosted a number of workshops to enhance collaborations among various experts in cetacean biology, marine ecosystems, modelling and climate change, as well as improving the conservation outcomes for cetaceans under climate change scenarios.

Future climate change-related challenges facing whale stocks require innovative, large-scale, long-term and multinational response from scientists, conservation managers and decision makers. Moreover, the reactions to emerging developments and changes will need to be swift (Simmonds & Eliott 2009).

Commission for the Conservation of Antarctic Marine Living Resources

The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) was established mainly in response to concerns that an increase in krill catches in the Southern Ocean could have a serious effect on populations of krill and other marine life, particularly on birds, marine mammals and fish, which depend on krill for food. Climate change is on the agenda of CCAMLR's Scientific Committee, which reports on this item to the commission. Climate change is also a factor the United States is considering in development of a proposal for a MPA in the Ross Sea. The United States would like to leave one area in the Ross Sea open to fishing and close an equivalent area so that the impacts of climate can be differentiated from the impacts of fishing.

North Pacific Marine Science Organization

The primary role of the North Pacific Marine Science Organization (PICES) is to promote and coordinate marine research undertaken by the parties (Canada, Japan, China, Korea, Russia, and the United States) in the temperate and sub-Arctic region of the North Pacific Ocean and its adjacent seas. It also endeavours to advance scientific knowledge about the ocean environment, global weather and climate change, living resources and their ecosystems, and the impacts of human activities as well as promote the collection and rapid exchange of scientific information on these issues. PICES provides an international forum to promote greater understanding of the biological and oceanographic processes of the North Pacific Ocean and its role in global environment.

PICES has published numerous scientific reports on the impacts of climate and climate change on fish species in the North Pacific, including reports forecasting climate impacts on future production of commercially exploited fish and shellfish (e.g., Hollowed et al. 2008). Since 2002, PICES has also hosted approximately 11 international symposia, 15 workshops, and 5 special sessions with climate change-related themes (see http://www.pices.int/publications/default.aspx).

Wider Caribbean Sea Turtle Conservation Network

The Wider Caribbean Sea Turtle Conservation Network (WIDECAST) is an active network of biologists, managers, community leaders and educators in more than 40 nations (including the United States) and territories committed to an integrated, regional capacity that ensures the recovery and sustainable management of depleted marine turtle populations. WIDECAST has conducted workshops geared towards marine turtle conservationists and MPA practitioners, covering climate-related topics, including monitoring, vulnerability assessment, selecting and prioritizing adaptation options and communicating climate change.

Climate change considerations by regional fisheries management organizations and living marine resource conservation organizations

In 2011, the United Nations General Assembly adopted a draft resolution (A/66/L.22) that expressed concern over the current and projected adverse effects of climate change on food security and the sustainability of fisheries. The resolution urged nations, either directly or through appropriate subregional, regional or global organizations or arrangements, to intensify efforts to assess and address, as appropriate, the impacts of global climate change on the sustainability of fish stocks and the habitats that support them.

Multilateral RFMOs in which the United States is a member are cognizant of the issue of climate change, but with few exceptions, most have done little to reduce the possible effects or develop contingency plans despite the growing body of fisheries research on climate change. None of the six existing bilateral fisheries agreements between the United States and neighbouring countries—five with Canada (albacore tuna, Pacific salmon, Pacific hake, Pacific halibut, and Great Lakes fisheries) and one with Russia (North Pacific and Bering Sea fisheries)—have formally addressed climate change issues. Bilateral fishing regimes undergo renegotiation periodically; the effects of climate change on fish stock range will have to be taken into consideration in these negotiations. The fishery governance process is much slower to adapt for an RFMO due to its consensus decision-making process, which is an additional complicating factor, especially if the RFMO has many member countries.

Straddling fish stocks

In some cases, changes in the location of straddling fish stocks may lead to challenges in international fisheries management. The United Nations defines straddling stocks as stocks of fish that migrate between, or occur in both, the EEZ of one or more states and the high seas (Figure 12). One example of such a challenge occurred within the US-Canada Pacific Salmon Commission (McIlgorm 2010). Pacific salmon are anadromous fish that cross state and international boundaries in their oceanic migrations. Fish spawned in the rivers of one jurisdiction are vulnerable to harvest in other jurisdictions. The turbulent history of US and Canadian cooperative management of their respective salmon harvests suggests that environmental variability may complicate the management of such shared resources. For 6 years, beginning in 1993, the United States and Canada were unable to agree on a full set of salmon-fishing regimes under the terms of the Treaty between the Government of Canada and the Government of the United States of America Concerning Pacific Salmon. The breakdown

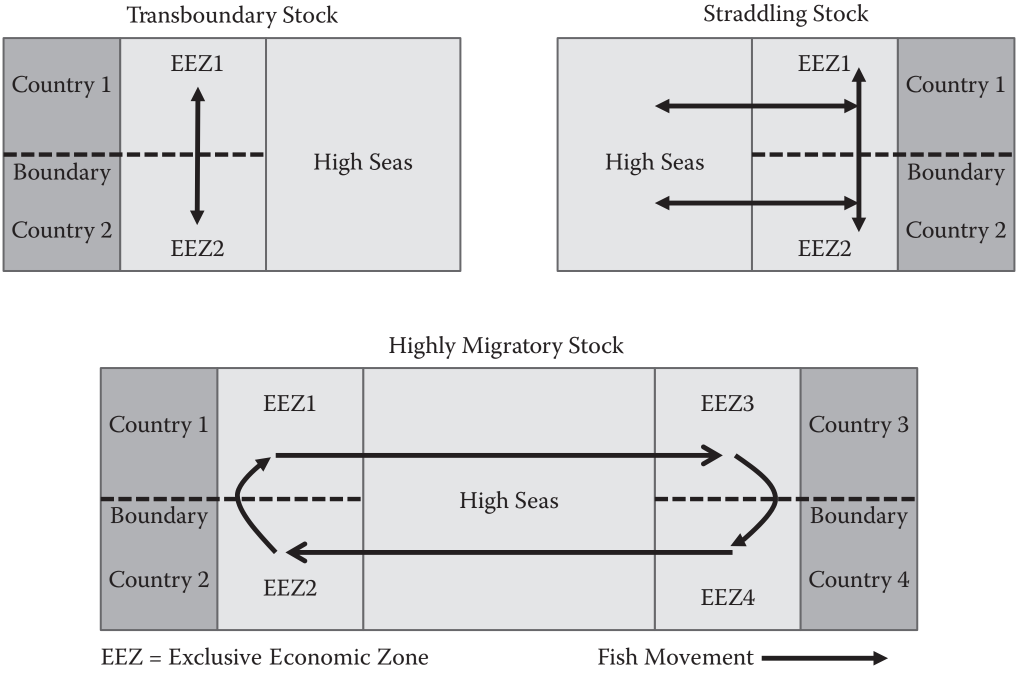


Figure 12 Types of fish stocks. Illustration of transboundary, straddling, and highly migratory species ranges.

in cooperation was fuelled by strongly divergent trends in Alaskan and southern salmon abundance and a consequent change in the balance of each nation's interceptions of salmon spawned in the other nation's rivers. A period of high productivity in Alaska contributed to increased Alaskan interceptions of British Columbia salmon at a time when Pacific North-west coho and Chinook salmon could least withstand additional actions by the Canadian salmon fleet. The mounting crisis led to a fundamental shift in the approach taken by the two nations to determine their respective salmon harvest shares. On 30 June 1999, Canada and the United States signed a 10-year agreement that laid the groundwork for a more sustainable and cooperative abundance-based management regime (Miller & Munro 2003). That agreement was renegotiated and extended for another 10 years in 2009. The latest agreement resulted in substantial investments in cooperative research programmes, improved modelling capabilities, and refined harvest rate calculations.

Future climate change will continue to have an impact on fisheries governance under the Pacific Salmon Treaty in the future as fisheries management science tries to assess the impacts of climate change on Pacific salmon (McIlgorm 2010).

Transboundary fish stocks

Climate change is also likely to have an impact on the spatial distribution of transboundary fish stocks. These are stocks that range in the EEZs of at least two countries (Figure 12), such as hake stocks off the US Atlantic and Pacific coasts, which both straddle the US-Canada border (Helser & Alade 2012). Pacific hake spawn off the coast of California and forage off the coasts of Oregon, Washington and Canada. Ocean conditions influence the latitudinal extent of Pacific hake and silver hake foraging migrations (Agostini et al. 2007, Nye et al. 2009). In addition, the age structure of the population also has a strong effect on the northerly distribution of Pacific hake; that is, older fish are found farther north in warm years. In 2003, the United States and Canada signed a treaty to establish national shares of the coastwide Pacific hake stock. Shares were initially determined by the percentage of the hake stock found in each country's waters during the summer fishing season. Shifts in spatial distribution of the foraging distribution will have an impact on the stock assessment and may necessitate changes to current management agreements for these stocks.

Another consideration is the lack of formal conservation and management agreements for transboundary fish stocks. Pacific sardines, which migrate across international boundaries, are a case in point. Currently, no international management agreement exists for Pacific sardines. However, scientists and members of industry from the United States, Mexico, and Canada informally meet at the annual Trinational Sardine Forum, where research results and ideas are exchanged. In view of the combined impact of fishing and ocean climate variability on the sardine stock, an important emerging issue is the need for stable transboundary management, given potential changes in the stock's availability within the affected countries' EEZs. The question becomes whether cooperative management of the stock will result in economic and biological gains to all three countries. If cooperative conservation and management involve a positive sum game, a related concern then becomes whether or not cooperative management will be stable in the face of climate change (Herrick et al. 2007).

Similar situations exist for a number of West Coast transboundary groundfish stocks, such as sablefish, petrale sole, and numerous rockfish species. These are currently managed separately by the US Pacific Fishery Management Council and Canada's Department of Fisheries and Oceans in British Columbia.

Highly migratory fish stocks

Some fish populations migrate over long distances, passing through multiple territorial waters (Figure 12). The term *highly migratory species* comes from Article 64 of UNCLOS. Although the convention does not provide an operational definition of the term, UNCLOS Annex 1 lists the species considered highly migratory by parties to the convention. The list includes tuna species (albacore, bluefin, bigeye, skipjack, yellowfin, blackfin, little tunny, southern bluefin and bullet) and tuna-like species (pomfret, marlin, sailfish, swordfish, saury and ocean-going sharks, dolphins and other cetaceans).

The stability and success of RFMOs that govern the harvests of straddling and highly migratory fish stocks will depend, in part, on how effectively they can maintain member nations' incentives to cooperate, despite the uncertainties and shifting opportunities that may result from climate-driven changes in productivity, migratory behaviour or catchability of the fish stocks governed by the RFMO (Miller 2007).

The reliance of island nations on tuna fisheries, and the potential adverse effects of climate change on this resource, emphasizes the need for precautionary approaches to management. The Western and Central Pacific are complex ocean fisheries with island nations and foreign fishers, including the United States, taking purse seine and longline tuna catches in areas to the north and east of Papua New Guinea. Independent states in the Pacific have several regional organizations, such as the South Pacific Forum Fisheries Agency (FFA) and the Western and Central Pacific Fishery Commission. The majority of fishery production is by distant water fishing nations under access agreements to FFA member states. Gaining economic benefits from domestic tuna fishery processing by island states is a priority to supplement income from access license fees.

Tuna are relatively sensitive to ocean temperature and move quickly to areas of preferred temperature. Consequently, the total stock of tuna does not necessarily change dramatically if temperature changes, but the spatial distribution may shift substantially (Aaheim & Sygna 2000). Climate change will have an impact on all industrial fishers and processors due to changes in the location of fishing sites, with vessels spending several months of the year inside a national EEZ as fish move to the high seas or to an adjacent EEZ. This movement has implications for licensing of foreign fishing vessels and tuna canneries using local suppliers. The increased risk of fish availability will have implications for future capital investment and labour requirements. Fishery governance systems need to be aware of potential climate change impacts on annual catches and the location of fish schools, increasing the variability in an already-complex system (McIlgorm 2010).

Arctic

Climate change is expected to have profound impacts in the Arctic; some of these changes are already being observed. The loss of sea ice is expected to have an impact on the timing of seasonal production and extend the growing season. Expansion or movement of some sub-Arctic species into the Arctic may occur over time, and the rates of expansion and movement will differ by species in relation to their vulnerability to climate change. There is a potential for expansion of fishing in response to periods of reduced ice cover in the Chukchi and Beaufort Seas. In recognition of this possibility, the NPFMC acted swiftly to close the US Arctic EEZ to commercial fishing until sufficient information is obtained to manage the stocks sustainably (Wilson & Ormseth 2009). While this action protects stocks within the US Arctic EEZ, the Arctic high-seas waters are international waters, and international fishing agreements may be needed for fisheries sustainability.

On a regional fisheries level, the potential for spatial displacement of aquatic resources and people as a result of climate change impacts will require existing regional structures and processes to be strengthened or enhanced. Agreements, both multilateral and bilateral, will need flexibility to adapt to changing circumstances, particularly unanticipated, climate-driven changes in stock levels or distribution across EEZs or high-seas areas.

Blue carbon

Blue carbon is a term to describe the carbon dioxide sequestered by seagrasses, tidal marshes, and mangroves and stored in large quantities in both the plants and in the sediment of coastal and marine ecosystems. Accounting for the carbon sequestration value of coastal marine systems has the potential to be a transformational tool in the implementation of improved coastal policy and management. Currently, no policy, financing, management or other systems specifically value the role of marine and coastal ecosystems in sequestering greenhouse gases or the potential emissions that result from degradation or conversion of these systems. There is, however, increasing attention on carbon sequestration in blue carbon systems both within the United States and internationally.

While not specifically dealing with blue carbon, a number of policy and financing mechanisms currently exist that support nature-based climate change mitigation solutions under UNFCCC, for example, Reducing Emissions from Deforestation and Forest Degradation (REDD+), National Appropriate Mitigation Actions (NAMAs), and the Clean Development Mechanisms (CDM) and Land-Use, Land-Use Change and Forestry (LULUCF) (Climate Focus 2011). These mechanisms provide incentives and financial support for national-level accounting and project-level activities, including conservation, restoration and sustainable use of natural systems such as forests and peatlands. Coastal ecosystems can be integrated into these existing UNFCCC-supported mechanisms.

There is a recognized need for increasing decision-maker awareness of the importance of coastal carbon, and to that end, UNFCCC has invited the submission of information on emissions from coastal and marine ecosystems (UNFCCC 2011). The IPCC has also established an expert working group to update the 2006 IPCC guidelines for including wetlands in national greenhouse gas inventories. This revision will include a chapter on ‘coastal wetlands’, previously absent (IPCC 2011).

The Blue Carbon Initiative is a global agenda to maintain the blue carbon stored in coastal ecosystems and avoid emissions from their destruction. The initiative, coordinated by Conservation International (CI), the International Union for Conservation of Nature (IUCN), and the Intergovernmental Oceanic Commission (IOC) of UNESCO, has established international expert working groups to develop (1) the necessary scientific basis and tools and (2) the international- and national-level policy frameworks needed to support blue carbon-based policy, management, conservation and science globally. Field-based demonstration projects have been identified by the working groups as a current priority to demonstrating the viability of blue carbon projects, facilitating the development of practical, science-based methodologies and building capacity in target countries.

The Verified Carbon Standard, an international carbon registry, is updating its requirements to provide for the inclusion of eligible wetlands projects for carbon financing. A number of countries, including Indonesia, Costa Rica and Ecuador, have identified blue carbon as a priority issue and are currently developing strategies and approaches. A number of US federal agencies are currently investigating the integration of coastal blue carbon into their priority activities. These countries are in need of technical and resource support to complete this process and implement effective coastal-carbon-based management and policy.

Climate change and other international issues

Climate change impacts on ocean services in the United States are provoking discussion on the future of ocean governance, including marine resource and ecosystem-based management. Perhaps the most noteworthy issue in this arena is the increase in shipping accessibility in the Arctic. National security concerns and threats to national sovereignty have also been a recent focus of attention (Campbell et al. 2007, Borgerson 2008, Lackenbauer 2011). According to some researchers, the Arctic region could slide into a new era, featuring jurisdictional conflicts and increasingly severe clashes over the extraction of natural resources among the global powers (Berkman & Young 2009). Others are confident that existing bilateral and international arrangements are robust enough to handle the new challenges. In any case, given that the effects of climate change will vary across regions of the United States and the world, diverse and novel governance and security challenges will likely emerge.

Climate change adaptation and mitigation actions often extend beyond regional scales and regional governance and security concerns. In general, the warming of the ocean is leading to a redrawing of the biophysical map of Earth. This process will lead to an expanded geopolitical discussion involving the relationship among politics, territory, and state sovereignty on local, national and international scales (Nuttall & Callaghan 2000).

The topic of 'security' is a growing theme of global environmental change discussions, especially those focusing on climate change (Barnett 2006). Sea-level rise and extreme events could potentially lead to human migration, both within the United States and movement from other nations into the United States. In addition, climate-related impacts on international food security could lead to foreign conflict. The central role of the United States in emerging international discussions on the relationship between climate change and security response strategies centre around past precedent, with the United States showing immediate response to natural disasters both via the military and monetary aid (Campbell et al. 2007). In addition to energy security, global trade, terrorism, nuclear non-proliferation, and global poverty, global climate change may become a significant foreign policy and national security challenge as it complicates and exacerbates many more traditional security issues.

According to the Arctic Council's 2009 AMSA report, "The Arctic is now experiencing some of the most rapid and severe climate change on earth. … Of direct relevance to future Arctic marine activity, and to the AMSA, is that potentially accelerating Arctic sea ice retreat improves marine access throughout the Arctic Ocean" (AMSA 2009, p. 26). With sea ice receding in the Arctic as a result of warming temperatures, global shipping patterns are already changing and will continue to change considerably in the decades to come (Cressey 2007, Stewart et al. 2007, Berkman & Young 2009, Khon et al. 2010).

As the Northern Sea Route and North-west Passage routes become more passable by vessels because of melting Arctic sea ice, these regions are experiencing greater maritime travel (Khon et al. 2010), and sailors are witnessing "an age-old dream come true" (Kerr 2002, p. 1490). This regional transformation has global economic implications. The international shipping industry influences much of current world trade, suggesting that increasing the capacity of maritime transport in the Arctic may highly affect the import and export of goods throughout the global economy. Furthermore, world seaborne trade is increasing, which is tightening the linkages among economic growth, trade, and demand for maritime transport services (Kitagawa 2008). Given this state of affairs, it is likely that climate change impacts on marine resources and users will involve direct and indirect challenges and opportunities for the US seaborne transportation sector.

Ocean management challenges, adaptation approaches, and opportunities in a changing climate

Individuals, communities, resource managers, and governments across the United States are beginning to understand, plan for, and address the impacts of climate change on oceans. While the practice of climate adaptation is relatively nascent (particularly for marine systems), strategies and actions are emerging. Adaptation planning requires access to best-available science, including long-term monitoring and assessment of environmental and societal change to understand baselines, track changes through time, and evaluate the effectiveness of actions. Tools and services are currently being developed to meet the growing demand for user-friendly, science-based information that supports ocean adaptation efforts. Two-way communication between scientists and practitioners is critical for ensuring that information meets the needs of decision makers.

Climate change presents not just a challenge but also an opportunity to revisit and improve existing plans and management strategies to make them more robust and forward looking. Integration of climate change into management and stewardship efforts, such as fishery management plans (FMPs) and the design of protected areas, will enhance ocean resilience. A key strategy is reducing non-climatic stressors (e.g., pollution, habitat destruction) to enhance ecosystem function and resilience to climate change. Existing legal and regulatory frameworks can also be leveraged to promote ocean adaptation efforts. Future success will depend on flexible, adaptive management that can accommodate uncertainty.

Challenges and opportunities for adaptation in marine systems

Adaptation involves the processes of preparing for and building resilience to climate change, as well as responding to unavoidable impacts (IPCC 2007, NRC 2010a). The climate impacts observed today will increase in severity in the future, even if greenhouse gas emissions are substantially limited in the near term (NRC 2010a). Therefore, climate change adaptation is a critical component of society's effort to foster a more sustainable future through enhancing the social, economic, and ecological resilience of ocean systems.

While diverse adaptation actions exist, most processes use the following general approach, as articulated by the NRC (2010a): identify relevant current and future climate changes, assess risks and vulnerabilities; develop and implement adaptation options; and create an iterative process by which adaptation actions can be re-evaluated and redesigned as necessary (Figure 13). Tenets of adaptation for ecosystem managers include protecting adequate and appropriate space, reducing non-climatic stressors that interact with the impacts of climate change, and adopting adaptive management practices (e.g., Hansen et al. 2010, Glick et al. 2011).

Compared to terrestrial, aquatic, and coastal systems, relatively few adaptation actions have been designed and implemented for marine systems. To better understand perceived and real barriers to action, a survey was conducted of North American coastal and marine managers, who articulated the following as barriers (Gregg et al. 2011):

- Lack of economic resources and budgetary constraints;
- Lack of institutional support, governance, and mandates to take adaptation action;
- Lack of institutional capacity and guidance on how to take action;

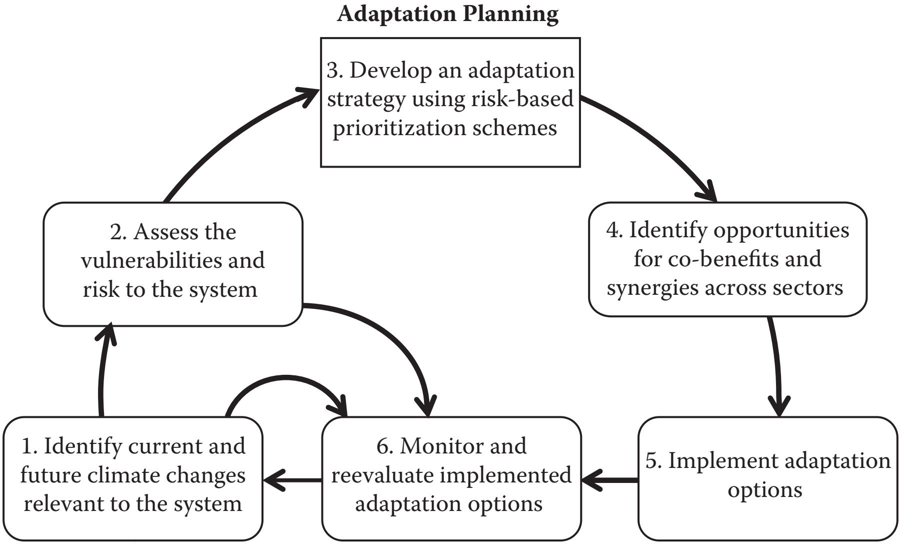


Figure 13 Conceptual framework for developing and implementing adaptation strategies. (From Stein et al. 2012.)

- Lack of key information on locally and regionally specific climate projections and tools to support assessments and monitoring;
- Uncertainty about risk and vulnerability; and
- Lack of awareness, stakeholder support, and engagement.

These constraints have been echoed by others (e.g., IPCC 2007, US Climate Change Science Program [CCSP] 2008, Glick et al. 2009).

Fortunately, solutions exist for overcoming many of these barriers, including enhanced provision of information, tools, and services that support ocean-related adaptation decisions and integration of climate change into existing policies, practices, and management.

Information, tools, and services to support ocean adaptation

Indicators, tools, and services are currently being developed to meet the growing demand for user-friendly, science-based information that supports ocean adaptation efforts. Incorporation of science is essential for successful adaptation planning, implementation, and evaluation. Decision makers rely on science to assess vulnerability and risk to a plausible range of climate change futures, understand potential impacts, inform adaptive actions, and evaluate the effectiveness of response options. Sustained interaction and feedback between scientists and information users (e.g., adaptation practitioners) can help to ensure that the information provided is accessible, understandable, and relevant. In addition, these interactions can grow the awareness of scientists regarding the key information needs of decision makers.

Importance of long-term observations and monitoring for adaptive management

The establishment of current baselines and trends is a core element of adaptation approaches (US CCSP 2008). Long-term data are essential for enhancing understanding of how ecosystems and human communities respond and adapt to climate change (Heinz Center 2008, Peterson & Baringer 2009). A range of observations on physical, ecological, social, and economic systems is needed to provide information on past and current trends, as well as to gain insight into future conditions. These observations not only detect changes and help communicate trends to managers and the public, but also are necessary for assessing risks, developing meaningful climate indices, and supporting adaptive management. Observations and monitoring data can provide critical insight into the relative contributions of anthropogenic change versus natural variability in ocean systems. In addition, long-term data can inform the development of more accurate and higher-resolution climate models that enhance the predictive capacity of managers and other decision makers.

Identification and accurate measurement of key variables can inform the development of ocean adaptation actions. Physical parameters (e.g., water temperature, water quality, salinity, pH and solar radiation; National Climate Assessment [NCA] 2010a); ecological parameters (e.g., phenology, species abundance and distribution, diversity and primary productivity; NCA 2010b); and socioeconomic parameters (e.g., demographics, food supplies, social and economic well-being and public health; NCA 2011) can help support assessments of vulnerability as well as the development of strategies for minimizing climate risks to ecosystems and communities. One opportunity is to leverage existing observation and monitoring systems, including those in MPAs, to establish ‘sentinel sites’ for understanding and managing for climate change (National Ocean Council 2012). For example, under the 1999 Marine Life Protection Act, and through a public-private partnership, California is implementing a statewide, 1100-mile network of MPAs to protect marine life, habitats, and ecosystems. The California Ocean Protection Council has invested over $20 million to conduct baseline characterizations of the ecosystem and to develop a novel approach for objective, scientifically rigorous, and cost-effective MPA monitoring. A statewide network of MPAs, in which other anthropogenic stressors are reduced, also provides a large-scale, natural laboratory to understand how climate changes manifest in ocean ecosystems. The innovative approaches to MPA monitoring being developed in the state also provide a framework that can be applied to inform the climate change management dialogue.

A challenge ahead is to ensure that coastal and ocean resource managers have access to high-quality information at resolutions commensurate with the scales at which decisions are made (Fauver 2008, National Ocean Council 2012). For example, oyster growers in the Pacific North-west depend on local observations to alert them to potentially harmful changes in ocean pH levels so that they can take proactive measures to protect young animals. Oceanographic models developed at the Woods Hole Oceanographic Institution and supported by long-term observations are now able to predict blooms of the toxic alga *Alexandrium fundyense*, providing local public officials and harvesters with an early-warning tool to minimize health risks and economic losses from tainted shellfish (Li et al. 2009). These examples illustrate the utility of accessible information at relevant decision scales.

Barriers remain in providing long-term information to support ocean adaptation decisions. There is a growing need to distill and synthesize large quantities of data into useful products that can provide practical information to inform management. The lack of a systematic approach to sustained, high-resolution climate observations is currently constraining the ability to develop informative and meaningful climate indices (NCA 2011). Efforts such as the Ocean Health Index offer a promising approach for synthesizing and improving accessibility of information on ocean stressors, as well as the valuable ecosystem services on which humans depend (Halpern et al. 2012). The index defines a healthy ocean as one that can sustainably deliver a range of benefits to people now and in the future and measures this health along 10 widely held public goals for the ocean and coasts, such as clean water, food provision, livelihoods, and cultural values. As such, the index provides assessments that are relevant to management objectives and mandates and allows systems that are sustainably used rather than simply protected to score highly. The index converts into a common measure the disparate ways in which climate impacts, fisheries production, pollution, species protection, coastal jobs, and other factors are assessed. The index can be used to assess the impacts of climate change on each of the 10 public goals, as well as the likely benefit to any given goal under management scenarios that target climate impact reduction versus improved fisheries management, land-based pollution regulations, or other measures (Halpern et al. 2012). User-friendly climate tools, services, and products based on long-term data will be essential for understanding changes and informing adaptation measures (Heinz Center 2008).

Tools and services for supporting ocean management in a changing climate

Efforts are under way to enhance the development and deployment of science in support of adaptation, to improve understanding and awareness of climate-related risks, and to enhance analytic capacity to translate understanding into planning and management activities (e.g., Moser & Luers 2008). For science to be useful to decision makers, the information provided must be timely, accessible, relevant, and credible. While critical knowledge gaps exist, there is a wealth of climate- and ocean-related science pertinent to adaptation. However, the majority of this information is currently 'inaccessible' to adaptation practitioners; it is unavailable, too technical to be understood and applied by non-scientists, or does not address the specific needs of decision makers. To address this challenge, diverse user-friendly tools and services are emerging, for example:

- The Sea Grant Climate Network is an online resource that includes adaptation-relevant information for coasts and oceans, a discussion forum, links to upcoming events, and social networking opportunities for the broader sea grant community, including extension agents. (http://sgcnetwork.ning.com/)
- Coral bleaching is a significant climate challenge for marine resource managers. Tools and services have been developed to help reef managers anticipate and respond to bleaching

events. For example, NOAA's Coral Reef Watch has developed several tools, including the Satellite Bleaching Alert system, an automated e-mail alert system that notifies subscribers when thermal conditions become conducive to bleaching at select reef sites. (http://coralfreewatch.noaa.gov/satellite/index.html)

- "Scanning the Conservation Horizon: A Guide to Climate Change Vulnerability Assessment" (Glick et al. 2011), produced by the National Wildlife Federation in partnership with the Department of Defense, the National Park Service, the US Fish and Wildlife Service (USFWS), the US Forest Service, NOAA, and the US Geological Survey, provides conservation practitioners and resource managers with methods and guidance for understanding and addressing the impacts of climate change on species and ecosystems. (http://www.nwf.org/~/media/PDFs/Global-Warming/Climate-Smart-Conservation/NWFScanningtheConservationHorizonFINAL92311.pdf?dmc=1&ts=20130317T1640584210)
- The Climate Adaptation Knowledge Exchange (CAKE), a joint project of Island Press and EcoAdapt, is aimed at building a shared knowledge base for managing natural systems, including oceans, in the face of climate change. (http://www.cakex.org/)
- The Coastal Climate Adaptation website of the NOAA Coastal Services Center provides diverse resources in support of coastal and ocean adaptation, such as state-level adaptation plans, case studies, climate communications information, risk and vulnerability assessments, guidance, and outreach materials. (http://collaborate.csc.noaa.gov/climateadaptation/default.aspx)

These tools and guidance documents help decision makers and managers navigate the complex landscape of information as they work to enhance preparedness and response efforts to safeguard ocean resources in a changing climate. The existing and emerging efforts to coordinate and provide timely, useful, and relevant climate information, tools, and services serve as a critical platform. However, a great deal of work remains in providing accessible information that meets the diverse set of adaptation planning, implementation, and evaluation challenges faced by marine resource managers and practitioners. Creative partnerships will be required in the near-term future to improve multidirectional communication and ensure that information provided by the scientific community meets the needs of decision makers.

Opportunities for integrating climate change into US ocean policy and management

While climate change presents challenges to marine resource managers and other ocean decision makers, solutions exist for incorporating climate change into ocean management. For example, because climatic and non-climatic stressors interact, reducing stressors over which there is more direct control (e.g., land-based pollution, habitat destruction) can enhance resilience to climate change and ocean acidification (Lubchenco & Petes 2010, Kelly et al. 2011). Next, we describe opportunities for reducing climate-related vulnerabilities of oceans by incorporating climate change considerations into marine spatial planning and MPA design, fisheries management, and application of existing legislative and regulatory frameworks.

Incorporating climate change into marine spatial planning and marine protected area design

Both coastal and marine spatial planning (CMSP) and MPAs spatially allocate human uses of the ocean as a means to better protect and sustainably use marine resources. CMSP focuses on all human uses of the oceans and seeks to allocate those uses across the ocean in a way that minimizes ecological, social, cultural, and economic impacts, while supporting and improving resource use and conservation goals (e.g., Ehler & Douvere 2009). MPAs instead focus primarily on limiting access to some or (in the case of 'no-take' marine reserves) all human uses within particular locations, typically for conservation or fisheries management purposes (e.g., Klein et al. 2008). Improving the enforcement and management of existing protected areas and refugia and increasing connectivity and the amount of protected space provide mechanisms for enhancing climate resilience (Glick et al. 2009). In addition, to enhance long-term effectiveness, it is critical that CMSP and MPA processes incorporate climate change into their planning, implementation, and evaluation efforts.

Accounting for the impacts of global climate change in CMSP and MPA planning may appear challenging as impacts can be diffuse and are often not under local control or management. However, there are at least three direct mechanisms for incorporating climate change into the design of management plans: (1) build resilience to climate impacts, (2) account for spatial patterns of climate impacts, and (3) anticipate future patterns of change.

Building climate resilience into spatial management remains the most commonly pursued approach (Halpern et al. 2008a, McLeod et al. 2009), in part because this mechanism is relatively straightforward and can leverage existing regulations and mandates. Targeted actions to limit or remove non-climatic stressors can help reduce the cumulative impact of total stressors, thus improving the ability of the ecosystem to cope with increases in climate-related stressors (Halpern et al. 2008b, 2010). For example, land-based pollution is the overwhelmingly dominant stressor to coastal areas of the Gulf of Mexico due to nutrient run-off from the human-dominated Mississippi River watershed, which drains into adjacent coastal areas (Halpern et al. 2009a). Efforts to reduce land-based stress would enhance resilience to climate impacts, such as sea-level rise, by improving the health of coastal salt marshes and wetlands. Furthermore, the size of protected areas or zones for limited use can be increased, and spacing between conservation patches decreased, as a means of buffering climate-related impacts (and other increasing or catastrophic stressors; e.g., Allison et al. 2003, McLeod et al. 2009). For example, the large areas encompassed by the MPAs recently established in the north-western Hawaiian Islands (Papahānaumokuākea Marine National Monument) and US Pacific holdings (Marianas Trench, Rose Atoll, and Pacific Remote Islands National Marine Monuments) are protected from many human activities. Therefore, these MPAs may be more resilient to climate impacts than are areas subject to higher levels of non-climatic stress from human activities.

Equally important are efforts to account for smaller-scale variation in climate impacts when designing spatially explicit resource management. Patterns of existing and projected impacts of changing sea-surface temperature, ocean acidification, and sea-level rise can be highly variable (Halpern et al. 2008b, Burrows et al. 2011). For management with a conservation goal, as in the case of MPAs, one potential strategy is to place protected areas in locations that exhibit high resilience to climate change. As assessments designed to inform CMSP and MPA planning processes engage and inform more sectors and more comprehensive planning, these efforts will be better able to address costs, benefits, and trade-offs across multiple sectors (e.g., White et al. 2012).

Anticipating future patterns of climate impacts and using these predictions in CMSP and MPA design are the most challenging, primarily because of the difficulty in predicting small-scale patterns of future climate impacts. Projected shifts in species ranges and ocean circulation patterns can be used to anticipate where species will exist in the future, as well as the potential for population connectivity through larval transport. MPA planning and CMSP processes can be designed to both anticipate and facilitate the transition to new geographies through strategies such as the creation of 'stepping stone' reserves that offer refuge or habitat to species as they migrate in response to warming waters (McLeod et al. 2009). In some cases, implementing networks of MPAs may help to diffuse climate risks by protecting multiple replicates of the full range of habitats and ecological communities within an ecosystem (US CCSP 2008).

Integrating climate change into fisheries management

Climate-related processes are affecting, and will continue to affect, the production of fisheries resources in marine ecosystems under US jurisdiction and beyond (Cochrane et al. 2009, Doney et al. 2012). Fish resources may respond to climate change in a variety of ways (e.g., changes in mortality, migration, distribution), and these changes can have important ramifications for fishery population dynamics, the ability to assess the status of fish populations, and the validity of future stock forecasts and rebuilding plans (Kraak et al. 2009).

The future sustainability and adaptation of fish resources in a changing climate depends on understanding past, current, and projected future climate impacts, and incorporating this information into the scientific bases of fishery management decisions, so that decision makers can effectively respond to impacts on existing fisheries and take advantage of new opportunities as conditions change (Link et al. 2010, Sumaila et al. 2011). Although some progress is being made, much work remains to ensure that fisheries management can effectively prepare for and adapt to the impacts of climate change on fish resources, as well as the communities and economies that depend on them (Hare et al. 2010, Link et al. 2010).

Most of the progress to date is in understanding climate impacts on fisheries. For example, in some US regions, oceanographic and fisheries observing systems are increasingly being mobilized to monitor and track the impacts of climate variability and change on fish and other living marine resources. These observing systems have been instrumental in producing the growing number of studies documenting persistent changes in spatial distribution of fishes attributable to large-scale changes in oceanographic processes (Nye et al. 2009, 2011, Link et al. 2010, Overholtz et al. 2011). The development of ‘marine ecosystem status reports’ in some regions is also providing a key mechanism for compiling and assessing marine ecosystem conditions as part of efforts to move towards ecosystem-based management (EAP 2009).

An increasing number of efforts are under way to understand and project the risks and impacts of climate variability and change on fish populations, as well as to advance modelling tools and their application to fisheries management (e.g., Hollowed et al. 2009, Stock et al. 2011). For example, Hollowed et al. (2009) developed and tested a framework for modelling fish and shellfish responses to future climate change. Mueter et al. (2011a) applied a variety of modelling techniques to project negative impacts of climate change (e.g., reduced recruitment) on walleye pollock populations in the Bering Sea. Another promising step is the development of ecosystem models to help explore the complex dynamics of marine ecosystems in a changing climate (Link et al. 2010). In addition, there is a growing body of literature and tools for assessing the vulnerability of natural resources in a changing climate (e.g., Glick et al. 2011). While most of this work has historically focused on terrestrial or freshwater environments, there has been some recent effort to develop and conduct vulnerability assessments for marine species (Johnson & Welch 2010).

There are relatively few examples of fishery management efforts that have explicitly incorporated climate-related information, but these efforts are expected to increase as more information and tools on climate impacts and vulnerabilities become available. The key questions remaining are: What are the adaptation options available to fisheries managers, and how and when should they be applied? At present, there appears to be little information and guidance to support fisheries management decisions along this path. Link et al. (2011) provided guidelines for incorporating distribution shifts into fisheries management, concluding that their approach is “feasible with existing information, and as such, fisheries managers should be able to begin addressing the role of changes in stock distribution in these fish stocks” (p. 461). Consideration of climate impacts on fishery resources will likely become more common with the development and application of ecosystem-based approaches, through mechanisms such as integration of changing environmental and ecological conditions into FMPs.

Efforts to integrate climate considerations into existing legislative and regulatory frameworks

Recent years have witnessed an increase in awareness that climate strategies must include efforts to both limit and adapt to climate change (e.g., Lazarus 2009, Ruhl 2010). Regulatory and management frameworks must be able to operate and remain effective in the face of increased and potentially significant uncertainty and change (Craig 2010, Gregg et al. 2011). While no single piece of existing US federal legislation directly targets climate change adaptation in the marine environment, there are several potential mechanisms, some of which are already being implemented, for incorporating climate change considerations into existing statutory and regulatory processes (e.g., Sussman et al. 2010, Gregg et al. 2011). As noted by the GAO, federal resource management agencies "are generally authorized … to address changes in resource conditions resulting from climate change in their management activities" (US GAO 2007, p. 2). Whether agencies are required to address climate change depends on their delegated statutory and regulatory authority.

Broadly applicable policy initiatives may enable climate change adaptation in the ocean and marine environment. For example, the National Ocean Council has developed draft implementation plans for two relevant national priority objectives: (1) "resiliency and adaptation to climate change and ocean acidification" and (2) "changing conditions in the Arctic" (NOC 2012). The Council on Environmental Quality (CEQ) has also drafted guidance for federal agencies on incorporating consideration of greenhouse gas emissions and adaptation measures into environmental reviews conducted pursuant to the National Environmental Policy Act (CEQ 2010, NEPA 42 U.S.C. § 4321 et seq.).

In addition, the United States is undertaking specific efforts to address adaptation to climate change impacts in the marine environment through existing legislative and regulatory frameworks. The following discussion describes efforts related to incorporating climate change considerations into regulation and management.

Ocean acidification The Clean Water Act (CWA) has been cited as a potential mechanism for managing climate change impacts in US waters (e.g., Craig 2009, Kelly et al. 2011). The purpose of the CWA is to restore and maintain the chemical, physical, and biological integrity of US waters (CWA 33 U.S.C. § 1251 et seq.). One of the statutory tools that may help manage ocean acidification is the designation of impaired waters, the designation for water bodies that fail to meet specified water quality standards. Pursuant to a settlement between the CBD and the EPA, the EPA solicited input on state approaches to determining whether waters are threatened or impaired by ocean acidification (*CBD v. EPA* 2009, *Federal Register* 2010a). The result was the agency's reassertion that states should seek scientific information on impacts and, when sufficient information is available, list as impaired those water bodies for which pH is below the recommended range (CWA § 304(a), US EPA 2010, Kelly et al. 2011). States can also list as impaired water bodies that fail to meet biological water quality standards because of ocean acidification, that is, water bodies that are failing to meet criteria established for coral reef ecosystems, bivalves, or other organisms protected under CWA aquatic life-designated uses (Bradley et al. 2010).

Threatened and endangered species Public and private efforts have worked to ensure consideration of climate impacts through protected species management laws and listing decisions. In accordance with the Endangered Species Act (16 U.S.C. § 1531 et seq.), NOAA and the USFWS designate, protect, and recover threatened and endangered species. These agencies cited climate change impacts, such as increased sea-surface temperatures, sea-level rise, loss of sea ice, and ocean acidification, as habitat stressors in their decisions to list as threatened elkhorn and staghorn coral species (*Federal Register* 2006), polar bears (*Federal Register* 2008), and the southern distinct population segment of the spotted seal (*Federal Register* 2010b), as well as the finding that listing of the Pacific walrus as threatened or endangered is warranted (*Federal Register* 2011). NOAA also identified climate change as a key factor in finding that a threatened or endangered listing may be warranted for 82 coral species (*Federal Register* 2010c). In addition to listings, agencies could factor climate adaptation considerations into critical habitat designations, recovery plans, and consultations on proposed federal actions (Kostyack & Rohlf 2008, Craig 2009, Owen 2012).

Fisheries management The MSA (16 U.S.C. §1801 et seq.) requires regional fishery management councils to develop FMPs, which must be approved by the secretary of commerce. While there are currently no requirements specifying consideration of climate change in FMPs, at least one regional council has begun to consider such impacts. In 2009, the NPFMC issued an FMP that closed Arctic fisheries to commercial harvesting (NPFMC 2009). Recognizing that loss of sea ice could remove barriers to previously inaccessible fisheries, the Arctic FMP established a prohibition against commercial fishing until adequate information is available to support sustainable management (NPFMC 2009). The decision reflects a precautionary approach to managing and developing fisheries in the face of climate change.

Enhancing the resilience of the nation's oceans to climate change will require action at all levels. The US federal statutory, regulatory, and policy efforts represent some of the existing approaches that agencies are taking to support adaptation to and management of climate change impacts in the marine environment.

Emerging frameworks and actions for ocean adaptation

Although the science and practice of marine adaptation are relatively nascent, many individuals, communities, ecosystem managers, and governments across the United States are developing strategies for enhancing ocean resilience in the face of a changing climate. Adaptation frameworks, including ocean-related adaptation efforts, are emerging across the US federal government (Center for Climate and Energy Solutions 2012). In addition, diverse frameworks for ocean adaptation action have been developed at national, regional, state, local, and non-governmental levels (Table 7). These efforts provide a platform to inspire and support the planning and implementation of on-the-ground actions.

Incorporation of climate change into forward-looking, adaptive management actions is beginning to occur for marine systems throughout the United States. For example, the North Pacific Climate Regimes and Ecosystem Productivity (NPCREP) project is working closely with resource managers to understand and address impacts of climate change on North Pacific and Bering Sea ecosystems. From 2000 to 2005, anomalously high sea-surface temperatures in the Bering Sea coincided with low pollock recruitment. NPCREP provided supplemental information that when considered in concert with the fisheries stock assessment corroborated the evidence that pollock recruitment was below average and added conservation was recommended. This information helped to inform the decisions of the NPFMC's Scientific and Statistical Committee. Based on recommendations from the committee, the NPFMC temporarily reduced pollock quotas between 2006 and 2010 until conditions became more favourable. This effort illustrates adaptive management based on changing environmental conditions.

To understand and address climatic and non-climatic threats to coral reefs, the US Geological Survey's Coral Reef Ecosystem Studies (CREST) project is investigating drivers and trends of coral reef ecosystem change. CREST is conducting monitoring and research efforts in national parks (Dry Tortugas, Virgin Islands, Biscayne) and areas of the Florida Keys National Marine Sanctuary. Projects include habitat mapping, assessment of calcification change related to ocean acidification, identification of diseases, and improving understanding of reef responses to sea-level change, among others. This work will improve understanding about coral health, advance the ability to forecast future change, and guide management decisions.

Oyster producers in the Pacific North-west have been facing persistently low seed survival, in part due to acidified waters. These failures are resulting in low harvest rates and economic impacts to shellfish hatcheries. In response, the Pacific Coast Shellfish Growers Association and partners launched the Emergency Oyster Seed Project in Washington State to establish monitoring programmes in key estuaries, develop solutions for enhancing hatchery production, and identify resilient oyster genotypes. Some hatcheries are already implementing adaptive management practices by coordinating water intake to avoid periods of high acidity.

Table 7 Examples of ocean-related climate adaptation frameworks in the United States

Adaptation project	Description
National/federal	
Interagency Climate Change Adaptation Task Force (ICCATF)	The ICCATF was initiated in spring 2009 to determine progress on federal agency actions in support of national adaptation and to develop recommendations for additional actions. The ICCATF is composed of more than 20 federal agencies and executive branch offices and has involved more than 300 federal employees. One outcome of this effort is a mandate (under Executive Order 13514) for all federal agencies, including those with ocean-related responsibilities, to develop adaptation plans.
National Fish, Wildlife & Plants Climate Adaptation Strategy	The National Fish, Wildlife, & Plants Climate Adaptation Strategy, initiated through Congressional directive in 2009, is currently under development. The strategy provides a nationwide blueprint for coordinated action among federal, state, tribal, and non-governmental entities to safeguard the nation's valuable natural resources, including marine resources, in a changing climate. The draft strategy was released in January 2012 for public review and input. The final version was released in Spring 2013.
National Ocean Policy	The National Ocean Policy was created in July 2010 under Executive Order 13547 to form a comprehensive, integrated framework for the stewardship of the ocean, coasts, and Great Lakes of the United States. In January 2012, a draft implementation strategy was released, including a set of interagency actions and milestones focused on enhancing the resiliency of oceans to climate change and ocean acidification.
Regional	
West Coast Governors Alliance on Ocean Health	The US West Coast Governors launched an Agreement on Ocean Health in 2006 to create a framework for regional collaboration on protection and management of ocean and coastal resources. The alliance includes a Climate Change Action Coordination Team, which is initially focusing on a West Coast assessment of shoreline change and anticipated impacts to coastal areas and communities due to climate change over the next several decades. This effort will inform adaptation to climate change and coastal hazards.
State	
State of California Climate Adaptation Strategy	In 2009, recognizing the need to prepare for climate change, the state of California released its Climate Adaptation Strategy. The Coastal and Ocean Resources Working Group is currently working to implement components of the strategy through assessing the risks of sea-level rise, mapping susceptible transportation areas, and conducting vulnerability assessments, among other actions.
Massachusetts Climate Change Adaptation Report	In response to the state's Global Warming Solutions Act of 2008, the secretary of energy and environmental affairs and the Massachusetts Climate Change Adaptation Advisory Committee produced the Massachusetts Climate Change Adaptation Report to describe state-level climate impacts, vulnerabilities, and adaptation strategies for key sectors, including coastal zone and oceans.
Non-governmental	
Alaskan Marine Arctic Conservation Action Plan for the Chukchi and Beaufort Seas	The Nature Conservancy's Alaska chapter developed the Conservation Action Plan to guide the organization's management and conservation efforts in the region. Climate change is identified in the plan as the primary threat to the region's natural resources. An expert panel helped guide the selection of primary conservation targets (bowhead whales, ice-dependent marine mammals, seabirds, boulder patch communities, benthic fauna, fish). Recommendations include promoting adaptation strategies and ecosystem-based management, investing in baseline and long-term data collection, and identifying and protecting climate refugia, among others.
A Climate Change Action Plan for the Florida Reef System (2010–2015)	The Florida Reef Resilience Program, a public-private partnership, released a Climate Change Action Plan in 2010. Florida reefs are subject to non-climatic and climatic stressors that are degrading overall ecosystem resilience. Priority actions identified in the plan include expanding disturbance response monitoring throughout the Florida Reef Tract, developing a marine zoning plan to address non-climate stressors, decreasing negative user impacts from fishing and diving, mapping areas of high and low resilience to prioritize protection, and restoring resistant reefs. The plan can be adopted by reef managers into existing management plans.

These efforts represent only a handful of the emerging ocean adaptation activities under way in the United States. They demonstrate that while much work remains to be done, actions are taking place across a spectrum of adaptation-related efforts, from risk, impact, and vulnerability assessments; to the development of guidance and tools; to on-the-ground implementation. In general, most ocean-related adaptation activities are still in the phases of improving understanding of risks, impacts, and vulnerabilities; some are in planning phases; and a few are in implementation. However, this also means that we can expect to see more actions in the future as marine managers and decision makers advance through the process of adaptation.

Sustaining the assessment of climate impacts on oceans and marine resources

Based on current understanding and projections, it is likely that marine ecosystems under US and other jurisdictions will continue to be affected by climate change through a suite of changes in ocean physical, chemical, biological, social, and economic systems (Hollowed et al. 2011, Sumaila et al. 2011, Doney et al. 2012). Despite this foundation of information, many uncertainties and gaps remain in understanding the current and future impacts of climate change and ocean acidification on marine ecosystems (Doney et al. 2012). Assessing what is known about past, current and future impacts is a challenging task, and as this review has shown, scientific knowledge is critical for gaining insight into the effects of climate change on the ocean environment and what those changes mean for the economy, social, cultural and personal well-being of the US population and to the health of the ocean itself.

The current body of literature documenting the effects of climate change on the ocean is growing rapidly, and it is critical to enhance integration of new knowledge into public and private-sector responses locally, nationally and internationally. One area of great need is interdisciplinary research that brings together scientists studying the biophysical effects of climate change with social scientists to develop a much fuller understanding of both the biophysical and human dimensions of climate change.

Improving understanding and projections of climate change impacts on natural and managed ecosystems remains a critical challenge. It is difficult to forecast how species, habitats, ecosystems, economies, and nations will respond when confronted by environmental conditions that are often outside the range of conditions experienced today. Communicating how climate change and ocean acidification are impacting the world's oceans and ocean resources, particularly in those areas where changes are expected to be seen in both the short and long term, is vital. Scientists and policy makers are now beginning to think about how to prepare the nation for climate change. The following are next steps that, if taken, would greatly aid in addressing this challenge; this is not intended to be a comprehensive list, and items are not listed in priority order.

Observations and monitoring

Monitoring by ships, buoys, satellites, scientists in the field, and even narwhals and seals carrying monitoring devices provides data that are the foundation for documenting the conditions and trends in US coastal and ocean ecosystems over time. Continuation, and in some areas expansion, of these monitoring efforts is essential to track trends and provide robust early warnings of future changes. Many critical information gaps remain with respect to understanding and documenting the impacts of climate change on ocean systems. Key steps to advance this area include

- Increase capacity and coordination of existing observing systems to collect, synthesize and deliver integrated information on physical, chemical, biological and social/economic impacts of climate change on US marine ecosystems.
- Monitor impacts of climate change on oceanic circulation, extreme weather events (including tropical cyclone activity), stratification, and sea-level rise.

- Improve detection and early warning of climate variability and change for ocean systems.
- Identify and implement a set of core physical, biological, and societal indicators of the condition of marine ecosystems that can be used to track and assess the impacts of climate change and ocean acidification, as well as the effectiveness of mitigation and adaptation efforts, over time at regional-to-national scales.
- Conduct integrated monitoring of ocean ecosystem and related socioeconomic change.
- Develop integrated ocean-related human health early-warning systems through deployment of marine sensors for monitoring, updating of public health surveillance systems, and developing of risk communication tools and strategies.

Research

A strategic, use-inspired and integrated science agenda is necessary for informing and supporting efforts to prepare for and respond to a changing climate. Advancing understanding and application of new knowledge will require sustained dialogue, mutual information exchange, and feedback among scientists, decision makers, and information users. Critical research gaps include

- Investigating the degree to which marine organisms can acclimate and populations can genetically adapt to rapid environmental change.
- Determining the cumulative impacts of multiple stressors (both climatic and non-climatic) on marine organisms within ecologically relevant contexts and understand the underlying mechanisms through which these impacts occur.
- Supporting research on climate- and ocean-related social, behavioural, and economic science needs (e.g., assessing adaptation options and trade-offs, determining costs of action vs. inaction, designing effective governance processes, identifying thresholds and tipping points in social systems, investigating decision making under uncertainty).
- Creating an interdisciplinary research effort and community-based risk assessment of the effects of ocean acidification.
- Improving understanding and valuation of climate-related impacts on ocean ecosystem services.
- Advancing scientific knowledge and application of the role of blue carbon in climate and ocean systems.
- Developing and implementing methods for evaluating the effectiveness of adaptation actions to enable a flexible and responsive management approach.

Modelling

Models can serve as valuable tools for improving understanding, prediction, and projection of climate-related changes in ocean systems. However, there are currently critical information needs associated with climate and ocean modelling that, if addressed, would improve the ability of decision makers to plan for the future. Therefore, there is a growing need to

- Advance modelling and projection of the integrated impacts of climate change on ocean physical, chemical, biological, and social systems at finer spatial (e.g., regional) and temporal (e.g., decadal) scales most relevant for decision makers.
- Improve understanding and projection of sea-level rise (including the potential for rapid ice melt), changes in ocean currents, and stratification.
- Improve prediction of environmental and ecological conditions that lead to non-linearities and tipping points in coastal and marine ecosystems.
- Enhance the development of spatially explicit predictions of ecosystem responses to climate change (particularly for local-to-regional scales), including estimates of uncertainty.

- Develop local-to-regional scale projections of climate impacts on ocean tourism and recreation.
- Develop models of fleet dynamics, vessel operator income, and community social and economic impacts linked to biophysical models of climate-induced changes.
- Develop dynamic models that incorporate risk and uncertainty to inform decisions on investment in adaptation and mitigation measures for ocean systems.

Communication

Climate change is a global problem with wide-ranging impacts, and it is essential that climate-related information, as well as the information needs of decision makers, be communicated effectively across many groups, including scientists, citizen scientists, partners, educators, resource managers, and elected officials, among others. Therefore, there is a growing need to

- Increase the capacity for integrating, synthesizing and sharing data acquired at different levels of space, time, taxonomic resolution, and so on into useful forms for diverse information users to support informed decision making.
- Coordinate and increase communication between decision makers and science providers to ensure that the most critical information needs are being met related to impacts, vulnerabilities, and adaptation of ocean systems in a changing climate.
- Build and support mechanisms with neighbouring countries and other international partners for assessing and addressing impacts of climate change and ocean acidification on marine ecosystems.

This review has shown the impacts of climate-related change on ocean physical, chemical, biological, and human social systems in the United States. This review has also elaborated on questions that continue to dominate climate change discussions, such as the following:

- What climate-related changes have already occurred in US marine ecosystems?
- Why are these changes happening?
- What effects are anticipated in the near future?
- What are the long-term trends of climate change?
- What can be done to prepare for and reduce impacts?
- How is science informing planning and policy?

Meeting the challenges of climate change in general and climate change impacts on the marine environment and ocean services requires interdisciplinary efforts and strengthened connections between science and decision making now and in the years to come (Østreng 2010).

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