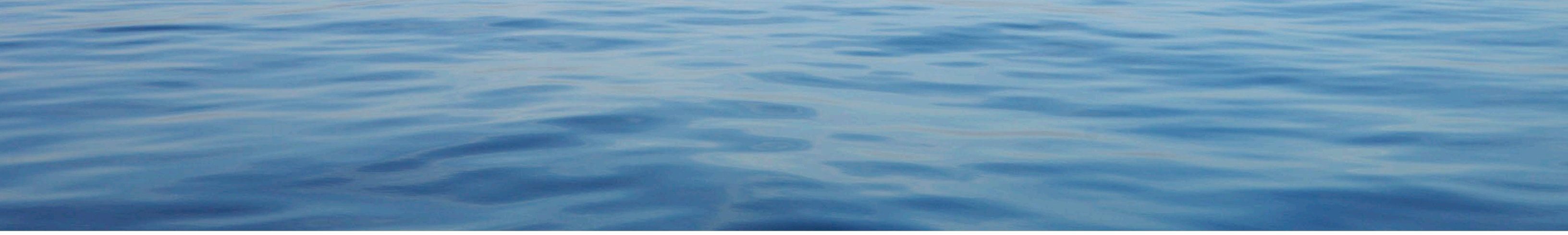

Climate Change Impacts in the United States

CHAPTER 24
OCEANS AND MARINE RESOURCES

Convening Lead Authors

Scott Doney, Woods Hole Oceanographic Institution

Andrew A. Rosenberg, Union of Concerned Scientists

Lead Authors

Michael Alexander, National Oceanic and Atmospheric Administration

Francisco Chavez, Monterey Bay Aquarium Research Institute

C. Drew Harvell, Cornell University

Gretchen Hofmann, University of California Santa Barbara

Michael Orbach, Duke University

Mary Ruckelshaus, Natural Capital Project

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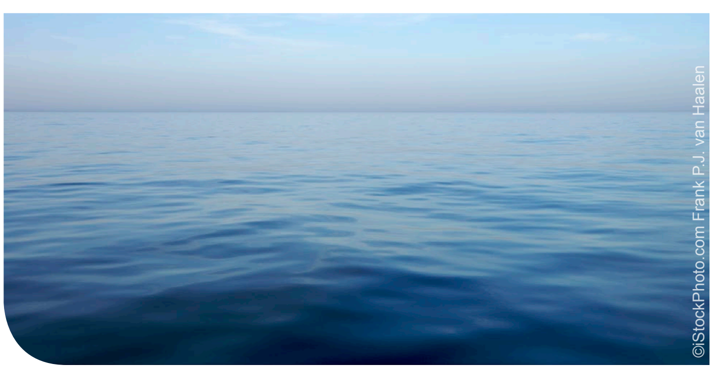
24 OCEANS AND MARINE RESOURCES

Key Messages

1. **The rise in ocean temperature over the last century will persist into the future, with continued large impacts on climate, ocean circulation, chemistry, and ecosystems.**
2. **The ocean currently absorbs about a quarter of human-caused carbon dioxide emissions to the atmosphere, leading to ocean acidification that will alter marine ecosystems in dramatic yet uncertain ways.**
3. **Significant habitat loss will continue to occur due to climate change for many species and areas, including Arctic and coral reef ecosystems, while habitat in other areas and for other species will expand. These changes will consequently alter the distribution, abundance, and productivity of many marine species.**
4. **Rising sea surface temperatures have been linked with increasing levels and ranges of diseases in humans and marine life, including corals, abalones, oysters, fishes, and marine mammals.**
5. **Climate changes that result in conditions substantially different from recent history may significantly increase costs to businesses as well as disrupt public access and enjoyment of ocean areas.**
6. **In response to observed and projected climate impacts, some existing ocean policies, practices, and management efforts are incorporating climate change impacts. These initiatives can serve as models for other efforts and ultimately enable people and communities to adapt to changing ocean conditions.**

As a nation, we depend on the oceans for seafood, recreation and tourism, cultural heritage, transportation of goods, and, increasingly, energy and other critical resources. The U.S. Exclusive Economic Zone extends 200 nautical miles seaward from the coasts, spanning an area about 1.7 times the land area of the continental U.S. and encompassing waters along the U.S. East, West, and Gulf coasts, around Alaska and Hawai'i, and including the U.S. territories in the Pacific and Caribbean. This vast region is host to a rich diversity of marine plants and animals and a wide range of ecosystems, from tropical coral reefs to Arctic waters covered with sea ice.



Oceans support vibrant economies and coastal communities with numerous businesses and jobs. More than 160 million people live in the coastal watershed counties of the United States, and population in this zone is expected to grow in the future. The oceans help regulate climate, absorb carbon dioxide (an important greenhouse, or heat-trapping, gas), and strongly influence weather patterns far into the continental interior. Ocean issues touch all of us in both direct and indirect ways.[1,2,3]

Changing climate conditions are already affecting these valuable marine ecosystems and the array of resources and services we derive from the sea. Some climate trends, such as rising seawater temperatures and ocean acidification, are common across much of the coastal areas and open ocean worldwide. The biological responses to climate change often vary from region to region, depending on the different combinations of species, habitats, and other attributes of local systems. Data records for the ocean are often shorter and less complete than those on land, and for many biological variables it is still difficult to discern long-term ocean trends from natural variability.[4]

Key Message 1: Rising Ocean Temperatures

The rise in ocean temperature over the last century will persist into the future, with continued large impacts on climate, ocean circulation, chemistry, and ecosystems.

Cores from corals, ocean sediments, ice records, and other indirect temperature measurements indicate the recent rapid increase of ocean temperature is the greatest that has occurred in at least the past millennium and can only be reproduced by climate models with the inclusion of human-caused sources of heat-trapping gas emissions.[5,6] The ocean is a critical reservoir for heat within Earth's climate system, and because of seawater's large heat storing capacity, small changes in ocean temperature reflect large changes in ocean heat storage. Direct measurements of ocean temperatures show warming beginning in about 1970 down to at least 2,300 feet, with stronger warming near the surface leading to increased thermal stratification (or layering) of the water column.[7,8] Sea surface temperatures in the North Atlantic and Pacific, including near U.S. coasts, have also increased since 1900.[9,10] In conjunction with a warming climate, the extent and thickness of Arctic sea ice has decreased rapidly over the past four decades.[11,12] Models that best match historical trends project seasonally ice-free northern waters by the 2030s.[13]

Climate-driven warming reduces vertical mixing of ocean water that brings nutrients up from deeper water, leading to potential impacts on biological productivity. Warming and altered ocean circulation are also expected to reduce the supply of oxygen to deeper waters, leading to future expansion of sub-surface low-oxygen zones.[15] Both reduced nutrients at the surface and reduced oxygen at depth have the potential to change ocean productivity.[14] Satellite observations indicate that warming of the upper ocean on year-to-year timescales leads to reductions in the biological productivity of tropical and subtropical (the region just outside the tropics) oceans and expansion of the area of surface waters with very low quantities of phytoplankton (microscopic marine plants) biomass.[16] Ecosystem models suggest that the same patterns of productivity change will occur over the next century as a consequence of warming during this century, perhaps also with increasing productivity near the poles.[17] These changes can affect ecosystems at multiple levels of the food web, with consequent changes for fisheries and other important human activities that depend on ocean productivity.[4,18]

Other changes in the physical and chemical properties of the ocean are also underway due to climate change. These include rising sea level,[19] changes in upper ocean salinity (including reduced salinity of Arctic surface waters) resulting from altered inputs of freshwater and losses from evaporation, changes in wave height from changes in wind speed, and changes in oxygen content at various depths – changes that will affect marine ecosystems and human uses of the ocean in the coming years.[4]

Observed Ocean Warming

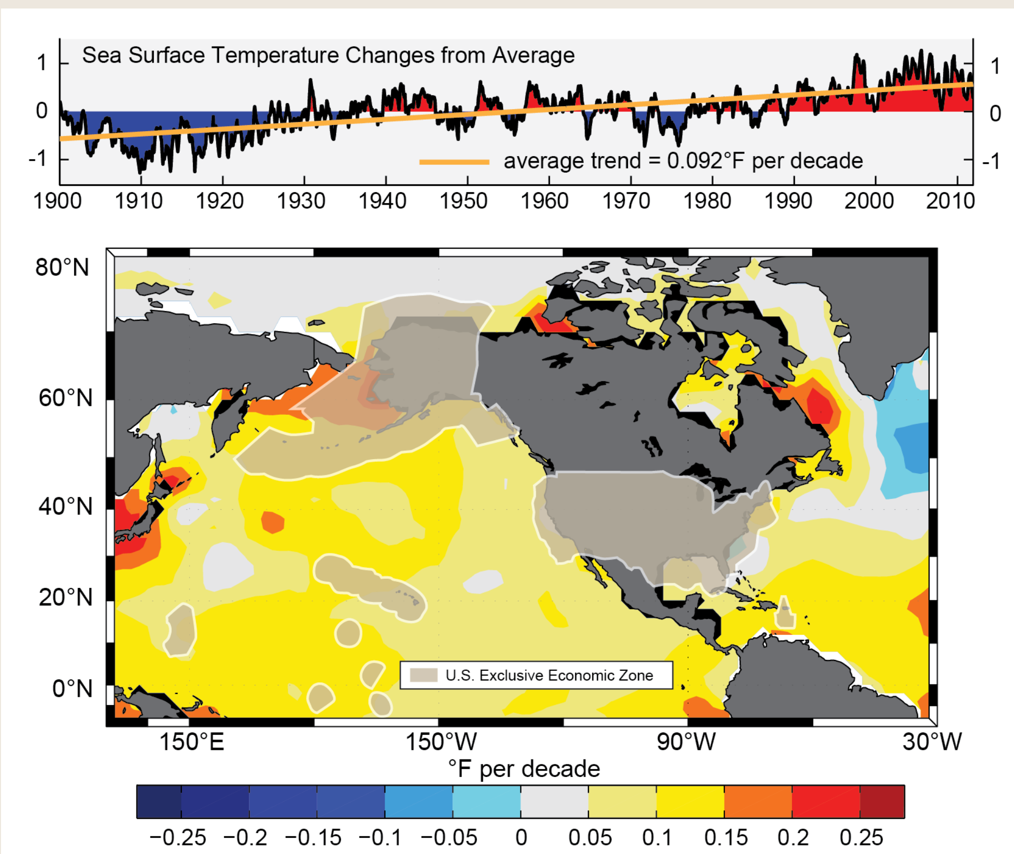


Figure 24.1. Sea surface temperatures for the ocean surrounding the U.S. and its territories have warmed by more than 0.9°F over the past century (top panel). There is significant variation from place to place, with the ocean off the coast of Alaska, for example, warming far more rapidly than other areas (bottom panel). The gray shading on the map denotes U.S. land territory and the regions where the U.S. has rights over the exploration and use of marine resources, as defined by the U.S. Exclusive Economic Zone (EEZ). (Figure source: adapted from Chavez et al. 2011[14]).

While the long-term global pattern is clear, there is considerable variability in the effects of climate change regionally and locally because oceanographic conditions are not uniform and are strongly influenced by natural climate fluctuations. Trends during short periods of a decade or so can be dominated by natural variability.[25] For example, the high incidence of La Niña events in the last 15 years has played a role in the observed temperature trends.[26]

Ocean Impacts of Increased Atmospheric Carbon Dioxide

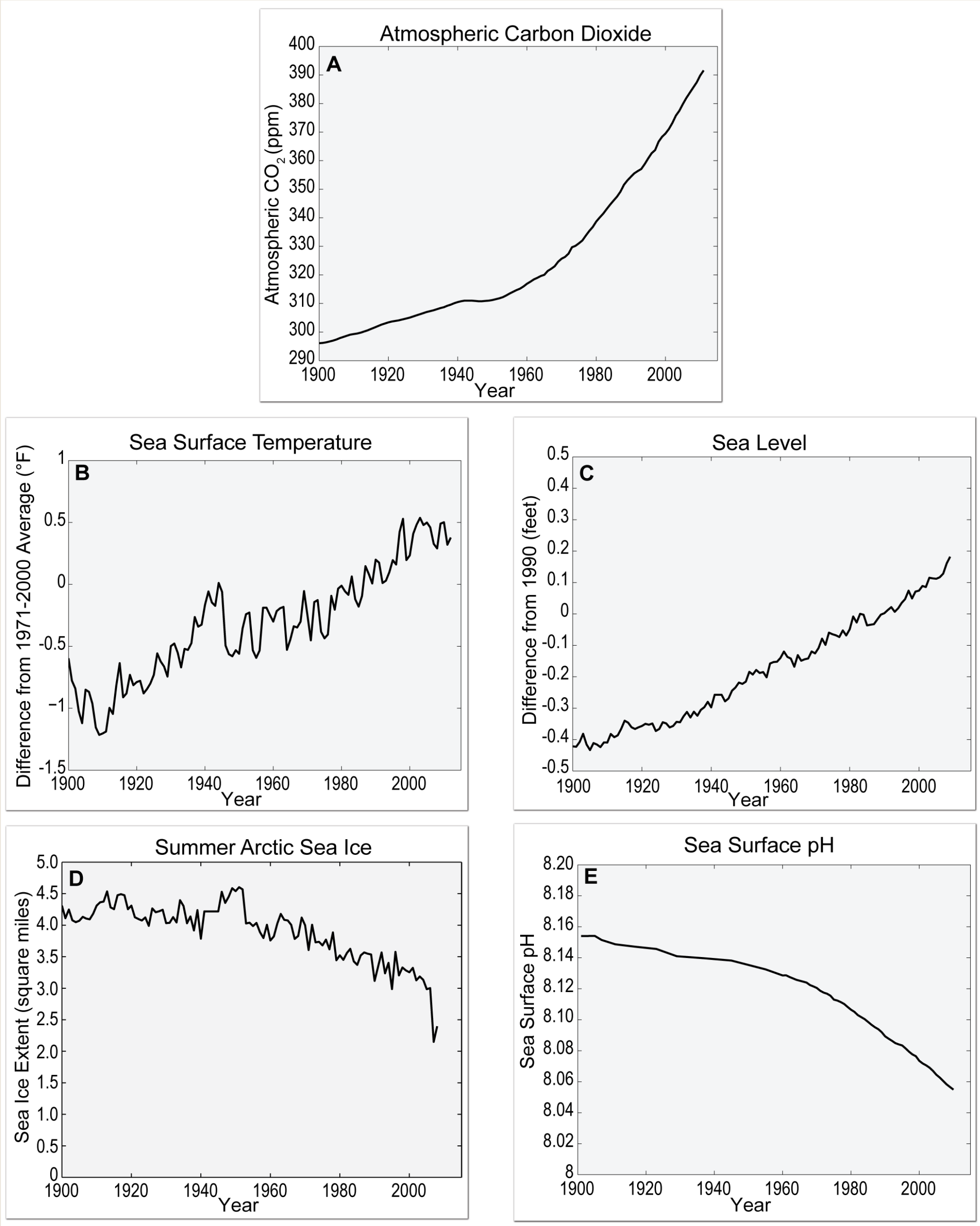


Figure 24.2. As heat-trapping gases, primarily *carbon dioxide (CO_2)* (panel A), have increased over the past decades, not only has air temperature increased worldwide, but so has the temperature of the ocean's surface (panel B). The increased ocean temperature, combined with melting of glaciers and ice sheets on land, is leading to higher sea levels (panel C). Increased air and ocean temperatures are also causing the continued, dramatic decline in Arctic sea ice during the summer (panel D). Additionally, the ocean is becoming more acidic as increased atmospheric *CO_2* dissolves into it (panel E). (CO_2 data from Etheridge 2010,[20] Tans and Keeling 2012,[21] and NOAA NCDC 2012;[22] SST data from NOAA NCDC 2012[22] and Smith et al. 2008;[10] Sea level data from CSIRO 2012[23] and Church and White 2011;[19] Sea ice data from University of Illinois 2012;[24] pH data from Doney et al. 2012[4]).

Analyses[27] suggest that more of the increase in heat energy during this period has been transferred to the deep ocean (see also Ch. 2: Our Changing Climate). While this might temporarily slow the rate of increase in surface air temperature, ultimately it will prolong the effects of global warming because the oceans hold heat for longer than the atmosphere does.

Interactions with processes in the atmosphere and on land, such as rainfall patterns and runoff, also vary by region and are strongly influenced by natural climate fluctuations, resulting in additional local variation in the observed effects in the ocean.

Marine ecosystems are also affected by other human-caused local and regional disturbances such as overfishing, coastal habitat loss, and pollution, and climate change impacts may exacerbate the effects of these other human factors.

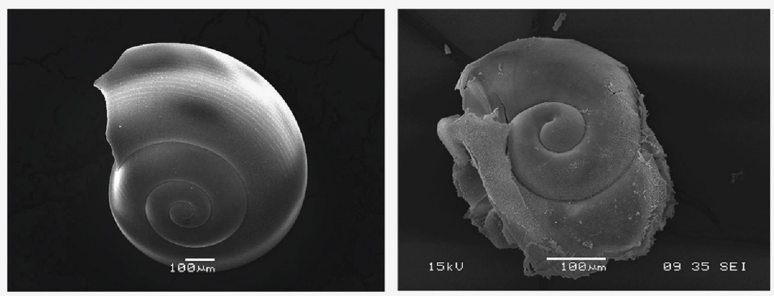
Key Message 2: Ocean Acidification Alters Marine Ecosystems

The ocean currently absorbs about a quarter of human-caused carbon dioxide emissions to the atmosphere, leading to ocean acidification that will alter marine ecosystems in dramatic yet uncertain ways.

Atmospheric carbon dioxide (CO_2) has risen by about 40% above pre-industrial levels.[21,28] The ocean absorbs about a quarter of human-caused emissions of carbon dioxide annually, thereby changing seawater chemistry and decreasing pH (making seawater more acidic) (Ch. 2: Our Changing Climate, Key Message 12).[3,29] Surface ocean pH has declined by 0.1 units, equivalent to a 30% increase in ocean acidity, since pre-industrial times.[30] Ocean acidification will continue in the future due to the interaction of atmospheric carbon dioxide and ocean water. Regional differences in ocean pH occur as a result of variability in regional or local conditions, such as upwelling that brings subsurface waters up to the surface.[31] Locally, coastal waters and estuaries can also exhibit acidification as the result of pollution and excess nutrient inputs.

Over 90% of seafood consumed in the U.S. is imported, and more than half of the imported seafood comes from aquaculture (fish and shellfish farming).[1] While only 1% of U.S. seafood comes from domestic shellfish farming, the industry is locally important. In addition, shellfish have historically been an important cultural and food resource for indigenous peoples along our coasts (Ch. 12: Indigenous Peoples, Key Message 1). Increased ocean acidification, low-oxygen events, and rising temperatures are already affecting shellfish aquaculture operations. Higher temperatures are predicted to increase aquaculture potential in poleward regions, but decrease it in the tropics.[37] Acidification, however, will likely reduce growth and survival of shellfish stocks in all regions.[34]

More acidic waters create repercussions along the marine food chain. For example, calcium carbonate is a skeletal component of a wide variety of organisms in the oceans, including corals. The chemical changes caused by the uptake of CO_2 make it more difficult for these living things to form and maintain calcium carbonate shells and skeletal components and increases erosion of coral reefs,[32] resulting in alterations in marine ecosystems that will become more severe as present-day trends in acidification continue or accelerate (Ch. 22: Alaska; Ch. 23: Hawai'i and Pacific Islands).[33,34,35] Tropical corals are particularly susceptible to the combination of ocean acidification and ocean warming, which would threaten the rich and biologically diverse coral reef habitats.



Pteropods, or "sea butterflies," are eaten by a variety of marine species ranging from tiny krill to salmon to whales. The photos show what happens to a pteropod's shell in seawater that is too acidic. On the left is a shell from a live pteropod from a region in the Southern Ocean where acidity is not too high. The shell on the right is from a pteropod in a region where the water is more acidic. (Photo credits: (left) Bednaršek et al. 2012;[105] (right) Nina Bednaršek).

Ocean Acidification Reduces Size of Clams

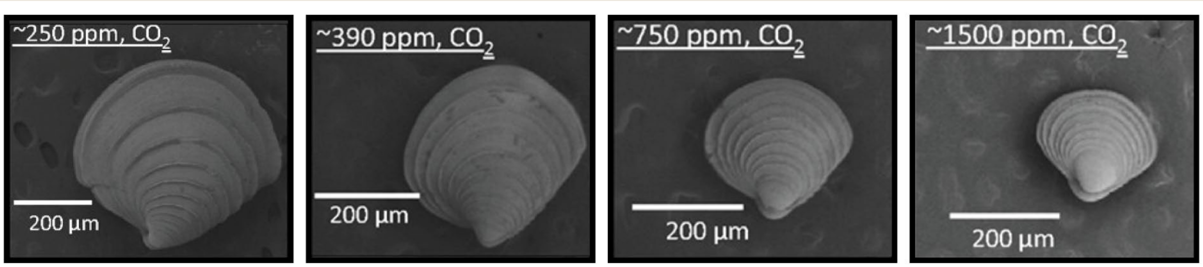


Figure 24.3. The 36-day-old clams in the photos are a single species, *Mercenaria mercenaria*, grown in the laboratory under varying levels of carbon dioxide (CO_2) in the air. CO_2 is absorbed from the air by ocean water, acidifying the water and thus reducing the ability of juvenile clams to grow their shells. As seen in the photos, where CO_2 levels rise progressively from left to right, 36-day-old clams (measured in microns) grown under elevated CO_2 levels are smaller than those grown under lower CO_2 levels. The highest CO_2 level, about 1500 parts per million (ppm; far right), is higher than most projections for the end of this century but could occur locally in some estuaries. (Figure source: Talmage and Gobler 2010[36]).

The impacts of ocean acidification on west coast aquaculture

Ocean acidification has already changed the way shellfish farmers on the West Coast conduct business. For oyster growers, the practical effect of the lowering pH of ocean water has not only been to make the water more acidic, but also more corrosive to young shellfish raised in aquaculture facilities. Growers at Whiskey Creek Hatchery, in Oregon's Netarts Bay, found that low pH seawater during spawning reduced growth in mid-stage larval (juvenile) Pacific oysters.[38] Hatcheries in Washington State have also experienced losses of spat (oyster larvae that have attached to a surface and begun to develop a shell) due to water quality issues that include other human-caused effects like dredging and pollution.[39] Facilities like the Taylor Shellfish Farms hatchery on Hood Canal have changed their production techniques to respond to increasing acidification in Puget Sound.

These impacts bring to light a potential challenge: existing natural variation may interact with human-caused changes to produce unanticipated results for shell-forming marine life, especially in coastal regions.[40] As a result, there is an increasing need for information about water chemistry conditions, such as data obtained through the use of sensor networks. In the case of Whiskey Creek, instruments installed in collaboration with ocean scientists created an "early warning" system that allows oyster growers to choose the time they take water into the hatchery from the coastal ocean. This allows them to avoid the lower-pH water related to upwelling and the commensurate loss of productivity in the hatchery.

From a biological perspective, these kinds of preventative measures can help produce higher-quality oysters. Studies on native Olympia oysters (*Ostrea lurida*) show that there is a "carry-over" effect of acidified water – oysters exposed to acidic conditions while in the juvenile stage continue to grow slower in later life stages.[41] Research on some oyster species such as Pacific oyster (*Crassostrea gigas*), the commercially important species in U.S. west coast aquaculture, shows that specially selected strains can be more resistant to acidification.[42]

Overall, economically important species such as oysters, mussels, and sea urchins are highly vulnerable to changes in ocean conditions brought on by climate change and rising atmospheric CO_2 levels. Sea temperature and acidification are expected to increase; the acidity of surface seawater is projected to nearly double by the end of this century. Some important cultured species may be influenced in larval and juvenile developing stages, during fertilization, and as adults,[43] resulting in lower productivity. Action groups, such as the California Current Acidification Network (C-CAN), are working to address the needs of the shellfish industry – both wild and aquaculture-based fisheries – in the face of ocean change. These efforts bring scientists from across disciplines together with aquaculturists, fishermen, the oceanographic community, and state and federal decision-makers to ensure a concerted, standardized, and cost-effective approach to gaining new understanding of the impact of acidification on ecosystems and the economy.[44]

Key Message 3: Habitat Loss Affects Marine Life

Significant habitat loss will continue to occur due to climate change for many species and areas, including Arctic and coral reef ecosystems, while habitat in other areas and for other species will expand. These changes will consequently alter the distribution, abundance, and productivity of many marine species.

Species have responded to climate change in part by shifting where they live.[45] Such range shifts result in ecosystem changes, including the relationships between species and their connection to habitat, because different species respond to changing conditions in different ways. This means that ocean ecosystems are changing in complex ways, with accompanying changes in ecosystem functions (such as nutrient cycling, productivity of species, and predator-prey relationships). Overall habitat extent is expected to change as well, though the degree of range migration will depend upon the life history of particular species. For example, reductions in seasonal sea-ice cover and higher surface temperatures may open up new habitats in polar regions for some important fish species, such as cod, herring, and pollock.[46] However, the continuing presence of cold bottom-water temperatures on the Alaskan Continental shelf could limit northward migration into the northern Bering Sea and Chukchi Sea.[47] In addition, warming may cause reductions in the abundance of some species, such as pollock, in their current ranges in the Bering Sea.[48] For other ice-dependent species, including several marine mammals such as polar bears, walruses, and many seal species, the loss of their critically important habitat will result in population declines.[49] Additionally, climate extremes can facilitate biological invasions by a variety of mechanisms such as increased movement or transport of invasive species, and decreased resilience of native species, so that climate change could increase existing impacts from human transport.[50] These changes will result in changing interactions among species with consequences that are difficult to predict. Tropical species and ecosystems may encounter similar difficulties in migrating poleward as success of some key species such as corals may be limited by adequate bottom substrate, water clarity, and light availability.[51]

Climate change impacts such as increasing ocean temperatures can profoundly affect production of natural stocks of fish by changing growth, reproduction, survival, and other critical characteristics of fish stocks and ecosystems. For species that migrate to freshwater from the sea, like salmon, some published studies indicate earlier start of spawning migration, warming stream temperatures, and extirpation in southern extent of range, all of which can affect productivity.[4,52] To remain within their normal temperature range, some fish stocks are moving poleward and to deeper water.[53,54] Fishery productivity is predicted to decline in the lower 48 states, but increase in parts of Alaska.[55] However, projections based only on temperature may neglect important food web effects. Fishing costs are predicted to increase as fisheries transition to new species and as processing plants and fishing jobs shift poleward.[18] The cumulative impact of such changes will be highly variable on regional scales because of the combination of factors – some acting in opposite directions. Some areas will benefit from range expansions of valuable species or increases in productivity, while others will suffer as species move away from previously productive areas.

Coral reef ecosystem collapse

Recent research indicates that 75% of the world's coral reefs are threatened due to the interactive effects of climate change and local sources of stress, such as overfishing, nutrient pollution, and disease.[56,57] In Florida, all reefs are rated as threatened, with significant impacts on valuable ecosystem services they provide.[58] Caribbean coral cover has decreased 80% in less than three decades.[59] These declines have in turn led to a flattening of the three dimensional structure of coral reefs and hence a decrease in the capacity of coral reefs to provide shelter and other resources for other reef-dependent ocean life.[60]

The relationship between coral and zooxanthellae (algae vital for reef-building corals) is disrupted by higher than usual temperatures and results in a condition where the coral is still alive, but devoid of all its color (bleaching). Bleached corals can later die or become infected with disease.[61,62] Thus, high temperature events alone can kill large stretches of coral reef, although cold water and poor water quality can also cause localized bleaching and death. Evidence suggests that relatively pristine reefs, with fewer human impacts and with intact fish and associated invertebrate communities, are more resilient to coral bleaching and disease.[63]

Warming Seas Are a Double-blow to Corals

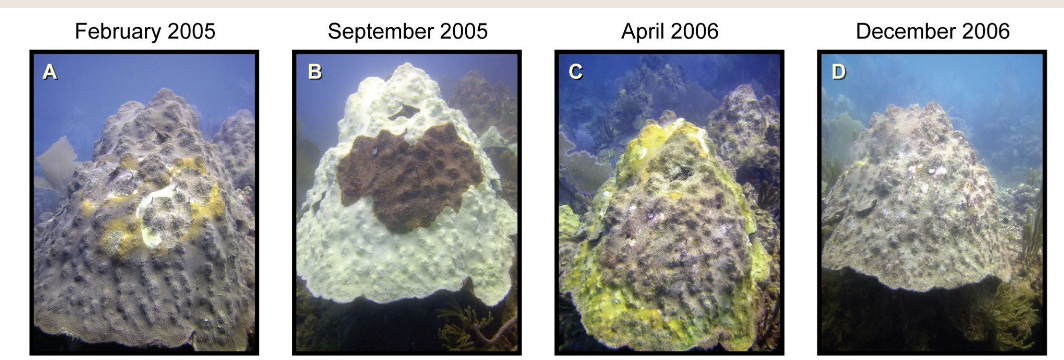


Figure 24.4. A colony of star coral (*Montastraea faveolata)* off the southwestern coast of Puerto Rico (estimated to be about 500 years old) exemplifies the effect of rising water temperatures. Increasing disease due to warming waters killed the central portion of the colony (yellow portion in A), followed by such high temperatures that bleaching - or loss of symbiotic algae from coral - occurred from the surrounding tissue (white area in B). The coral then experienced more disease in the bleached area on the periphery (C) that ultimately killed the colony (D). (Photo credit: Ernesto Weil).

Key Message 4: Rising Temperatures Linked to Diseases

Rising sea surface temperatures have been linked with increasing levels and ranges of diseases in humans and in marine life, including corals, abalones, oysters, fishes, and marine mammals.

There has been a significant increase in reported incidences of disease in corals, urchins, mollusks, marine mammals, turtles, and echinoderms (a group of some 70,000 marine species including sea stars, sea urchins, and sand dollars) over the last several decades.[64,65,66,67] Increasing disease outbreaks in the ocean affecting ecologically important species, which provide critically important habitat for other species such as corals,[65,68] algae,[69] and eelgrass,[70] have been linked with rising temperatures. Disease increases mortality and can reduce abundance for affected populations as well as fundamentally change ecosystems by changing habitat or species relationships. For example, loss of eelgrass beds due to disease can reduce critical nursery habitat for several species of commercially important fish.[70,71]

The complexity of the host/environment/pathogen interaction makes it challenging to separate climate warming from the myriad of other causes facilitating increased disease outbreaks in the ocean. However, three categories of disease-causing pathogens are unequivocally related to warming oceans. Firstly, warmer winters due to climate change can increase the overwinter survival and growth rates of pathogens.[67] A disease-causing parasite in oysters that proliferates at high water temperatures and high salinities spread northward up the eastern seaboard as water temperatures warmed during the 1990s.[72] Growth rates of coral disease lesions increased with winter and summer warming from 1996 to 2006.[62] Winter warming in the Arctic is resulting in increased incidence of a salmon disease in the Bering Sea and is now thought to be a cause of a 57% decline of Yukon Chinook salmon.[73]

Secondly, increasing disease outbreaks in ecologically important species like coral, eelgrass, and abalone have been linked with temperatures that are higher than the long-term averages. The spectacular biodiversity of tropical coral reefs is particularly vulnerable to warming because the corals that form the foundational reef structure live very near the upper temperature limit at which they thrive. The increasing frequency of record hot temperatures has caused widespread coral bleaching[66] and disease outbreaks[65] and is a principal factor contributing to the International Union for the Conservation of Nature listing a third of the reef-building corals as vulnerable, endangered, or critically endangered [74] and the National Oceanic and Atmospheric Administration proposing to list 66 species of corals under the Endangered Species Act.[75,76] In the Chesapeake Bay, eelgrass died out almost completely during the record-hot summers of 2005 and 2010,[77] and the California black abalone has been driven to the edge of extinction by a combination of warming water and bacterial disease.[78]

Thirdly, there is evidence that increased water temperature is responsible for the enhanced survival and growth of certain marine bacteria that make humans sick.[78] Increases in growth of *Vibrio parahaemolyticus* (a pathogenic bacterial species) during the warm season are responsible for human illnesses associated with oysters harvested from the Gulf of Mexico[79] and northern Europe.[80] *Vibrio vulnificus*, which is responsible for the overwhelming majority of reported seafood-related deaths in the United States,[81] is also a significant and growing source of potentially fatal wound infections associated with recreational swimming, fishing-related cuts, and seafood handling, and is most frequently found in water with a temperature above 68°F.[79,81,82]

Key Message 5: Economic Impacts of Marine-related Climate Change

Climate changes that result in conditions substantially different from recent history may significantly increase costs to businesses as well as disrupt public access and enjoyment of ocean areas.

Altered environmental conditions due to climate change will affect, in both positive and negative ways, human uses of the ocean, including transportation, resource use and extraction, leisure and tourism activities and industries, in the nearshore and offshore areas. Climate change will also affect maritime security and governance. Arctic-related national security concerns and threats to national sovereignty have also been a recent focus of attention for some researchers.[83,84] With sea ice receding in the Arctic as a result of rising temperatures, global shipping patterns are already changing and will continue to change considerably in the decades to come.[84,85] The increase in maritime traffic could make disputes over the legal status of sea lines-of-communication and international straits more pointed, but mechanisms exist to resolve these disputes peacefully through the Law of the Sea Convention and other customary international laws.

Resource use for fisheries, aquaculture, energy production, and other activities in ocean areas will also need to adjust to changing ocean climate conditions. In addition to the shift in habitat of living resources discussed above, changing ocean and weather conditions due to human-induced climate change make any activities at sea more difficult to plan, design, and operate.

In the United States, the healthy natural services (such as fishing and recreation) and cultural resources provided by the ocean also play a large economic role in our tourism industry. Nationally in 2010, 2.8% of gross domestic product, 7.52 million jobs, and $1.11 trillion in travel and recreational total sales are supported by tourism.[86] In 2009-2010, nine of the top ten states and U.S. territories and seven of the top ten cities visited by overseas travelers were coastal, including the Great Lakes. Changes in the location and distribution of marine resources (such as fish, healthy reefs, and marine mammals) due to climate change will affect the recreational industries and all the people that depend on reliable access to these resources in predictable locales. For example, as fish species shift poleward or to deeper waters,[54,87] these fish may be less accessible to recreational fishermen. Similar issues will also affect commercial fishing.

Similarly, new weather conditions differing from the historical pattern will pose a challenge for tourism, boating, recreational fishing, diving, and snorkeling, all of which rely on highly predictable, comfortable water and air temperatures and calm waters. For example, the strength of hurricanes and the number of strong (Category 4 and 5) hurricanes are projected to increase over the North Atlantic (Ch. 2: Our Changing Climate). Changes in wind patterns[88] and wave heights have been observed[89] and are projected to continue to change in the future.[90] This means that the public will not be able to rely on recent experience in planning leisure and tourism activities.[91,92] As weather patterns change and air and sea surface temperatures rise, preferred locations for recreation and tourism also may change. In addition, infrastructure such as marinas, marine supply stores, boardwalks, hotels, and restaurants that support leisure activities and tourism will be negatively affected by sea level rise. They may also be affected by increased storm intensity and changing wave heights,[92] as well as elevated storm surge due to sea level rise and other expected effects of a changing climate; these impacts will vary significantly by region.[93]

Key Message 6: Initiatives Serve as a Model

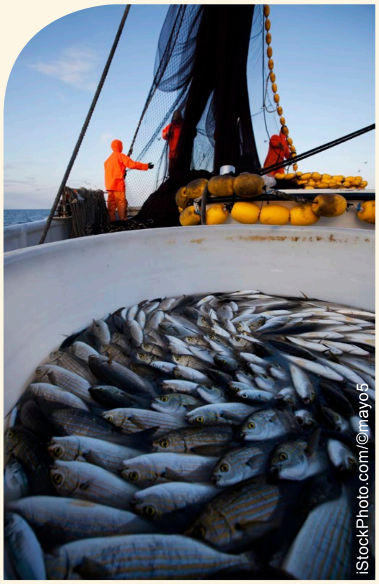
In response to observed and projected climate impacts, some existing ocean policies, practices, and management efforts are incorporating climate change impacts. These initiatives can serve as models for other efforts and ultimately enable people and communities to adapt to changing ocean conditions.

Climate considerations can be integrated into planning, restoration, design of marine protected areas, fisheries management, and aquaculture practices to enhance ocean resilience and adaptive capacity. Many existing sustainable-use strategies, such as ending overfishing, establishing protected areas, and conserving habitat, are known to increase resilience. Analyses of fishery management and climate scenarios suggest that adjustments to harvest regimes (especially reducing harvest rates of over-exploited species) can improve catch stability under changing climate conditions. These actions could have a greater effect on biological and economic performance in fisheries than impacts due to warming over the next 25 years.[94] The stability of international ocean and fisheries treaties, particularly those covering commercially exploited and critical species, might be threatened as the ocean changes.[95]

The fact that the climate is changing is beginning to be incorporated into existing management strategies. New five-year strategies for addressing flooding, shoreline erosion, and coastal storms have been developed by most coastal states under their Coastal Zone Management Act programs.[3] Many of these plans are explicitly taking into account future climate scenarios as part of their adaptation initiatives. The North Pacific Fishery Management Council and NOAA have declared a moratorium on most commercial fisheries in the U.S. Arctic pending sufficient understanding of the changing productivity of these fishing grounds as they become increasingly ice-free. Private shellfish aquaculture operations are changing their business plans to adapt to ocean acidification.[38,39] These changes include monitoring and altering the timing of spat settlement dependent on climate change induced conditions, as well as seeking alternative, acid-resistant strains for culturing. Marine protected areas in the National Marine Sanctuary (NMS) System are gradually preparing climate impact reports and climate adaptation action plans under their Climate Smart Sanctuary Initiative.[96]

Additionally, there is promise in restoring key habitats to provide a broad suite of benefits that can reduce climate impacts with relatively little ongoing maintenance costs (see Ch. 25: Coasts; Ch. 28: Adaptation). For example, if in addition to sea level rise, an oyster reef or mangrove restoration strategy also included fish habitat benefits for commercial and recreational uses and coastal protection services, the benefits to surrounding communities could multiply quickly. Coral-reef-based tourism can be more resilient to climate change impacts through protection and restoration, as well as reductions of pollution and other habitat-destroying activities. Developing alternative livelihood options as part of adaptation strategies for marine food-producing sectors can help reduce economic and social impacts of a changing climate.

Climate Impacts on New England Fisheries



Fishing in New England has been associated with bottom-dwelling fish for more than 400 years, and is a central part of the region's cultural identity and social fabric. Atlantic halibut, cod, haddock, flounders, hakes, pollock, plaice, and soles are included under the term "groundfish." The fishery is pursued by both small boats (less than 50 feet long) that are typically at sea for less than a day, and by large boats (longer than 50 feet) that fish for a day to a week at a time. These vessels use home ports in more than 100 coastal communities from Maine to New Jersey, and the landed value from fisheries in New England and the Mid-Atlantic in 2010 was nearly $1.2 billion.[76] Captains and crew are often second- or third-generation fishermen who have learned the trade from their families.

From 1982 to 2006, sea surface temperature in the coastal waters of the Northeast warmed by close to twice the global rate of warming over this period.[97] Long-term monitoring of bottom-dwelling fish communities in New England revealed that the abundance of warm-water species increased, while cool-water species decreased.[54,98] A recent study suggests that many species in this community have shifted their geographic distributions northward by up to 200 miles since 1968, though substantial variability among species also exists.[54] The northward shifts of these species are reflected in the fishery as well: landings and landed value of these species have shifted towards northern states such as Massachusetts and Maine, while southern states have seen declines (see Figure 24.5).

The economic and social impacts of these changes depend in large part on the response of the fishing communities in the region.[99] Communities have a range of strategies for coping with the inherent uncertainty and variability of fishing, including diversification among species and livelihoods, but climate change imposes both increased variability and sustained change that may push these fishermen beyond their ability to cope.[100] Larger fishing boats can follow the fish to a certain extent as they shift northward, while smaller inshore boats will be more likely to leave fishing or switch to new species.[100] Long-term viability of fisheries in the region may ultimately depend on a transition to new species that have shifted from regions farther south.[18]

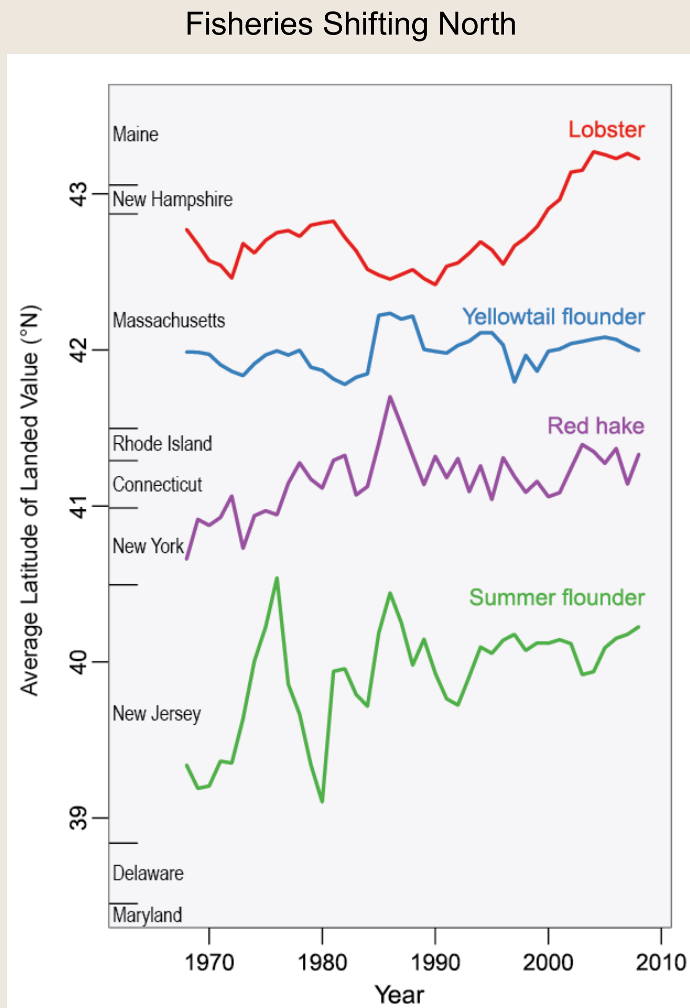


Figure 24.5. Ocean species are shifting northward along U.S. coastlines as ocean temperatures rise. As a result, over the past 40 years, more northern ports have gradually increased their landings of four marine species compared to the earlier pattern of landed value. While some species move northward out of an area, other species move in from the south. This kind of information can inform decisions about how to adapt to climate change. Such adaptations take time and have costs, as local knowledge and equipment are geared to the species that have long been present in an area. (Figure source: adapted from Pinsky and Fogerty 2012[101]).

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SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Traceable Accounts

Process for Developing Key Messages:

A central component of the assessment process was the Oceans and Marine Resources Climate assessment workshop that was held January 23-24, 2012, at the National Oceanographic and Atmospheric Administration (NOAA) in Silver Spring, MD, and simultaneously, via web teleconference, at NOAA in Seattle, WA. In the workshop, nearly 30 participants took part in a series of scoping presentations and breakout sessions that began the process leading to a foundational Technical Input Report (TIR) entitled "Oceans and Marine Resources in a Changing Climate: Technical Input to the 2013 National Climate Assessment."[102] The report, consisting of nearly 220 pages of text organized into 7 sections with numerous subsections and more than 1200 references, was assembled by 122 authors representing governmental agencies, non-governmental organizations, tribes, and other entities.

The chapter author team engaged in multiple technical discussions via teleconferences that permitted a careful review of the foundational TIR[102] and of approximately 25 additional technical inputs provided by the public, as well as the other published literature, and professional judgment. The chapter author team met at Conservation International in Arlington, VA on 3-4 May 2012 for expert deliberation of draft key messages by the authors, wherein each message was defended before the entire author team before the key message was selected for inclusion in the report. These discussions were supported by targeted consultation with additional experts by the lead author of each message to help define "key vulnerabilities."

Key message #1 Traceable Account

The rise in ocean temperature over the last century will persist into the future, with continued large impacts on climate, ocean circulation, chemistry, and ecosystems.

Description of evidence base

The key message is supported by extensive evidence documented in Sections 2 and 3 of the Oceans Technical Input Report[102] and in the additional technical inputs received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter.

Relevant and recent peer-reviewed publications,[5,7,8] including many others that are cited therein, describe evidence that ocean temperature has risen over the past century. This evidence base includes direct and indirect temperature measurements, paleoclimate records, and modeling results.

There are also many relevant and recent peer-reviewed publications describing changes in physical and chemical ocean properties that are underway due to climate change.[11,14]

New information and remaining uncertainties

Important new information since the last National Climate Assessment[103] includes the latest update to a data set of ocean temperatures.[7]

There is accumulating new information on all of these points with regard to physical and chemical changes in the ocean and resultant impacts on marine ecosystems. Both measurements and model results are continuing to sharpen the picture.

A significant area of uncertainty remains with regard to the region-by-region impacts of warming, acidification, and associated changes in the oceans. Regional and local conditions mean that impacts will not be uniform around the U.S. coasts or internationally. Forecasting of regional changes is still an area of very active research, though the overall patterns for some features are now clear.

Large-scale and recurring climate phenomena (such as the El Niño Southern Oscillation, the Pacific Decadal Oscillation, and the Atlantic Multidecadal Oscillation) cause dramatic changes in biological productivity and ecosystem structure and make it difficult to discern climate-driven trends.

Current time series of biological productivity are restricted to a handful of sites around the globe and to a few decades, and global, comprehensive satellite time series of ocean color are even shorter, beginning in 1997. Based on an analysis of different in situ datasets, one research group suggested a decline of 1% per year over the past century, but these findings may be an artifact of limited data and have been widely debated.[14,104] However, the few in situ time series mostly indicate increases in biological productivity over the past 20 years, but with clear links to regional changes in climate.[14]

Assessment of confidence based on evidence

Confidence that the ocean is warming and acidifying, and that sea level is rising is **very high**. Changes in other physical and chemical properties such as ocean circulation, wave heights, oxygen minimums, and salinity are of **medium** confidence. For ecosystem changes, there is **high** confidence that these are occurring and will persist and likely grow in the future, though the details of these changes are highly geographically variable.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Key message #2 Traceable Account

The ocean currently absorbs about a quarter of human-caused carbon dioxide emissions to the atmosphere, leading to ocean acidification that will alter marine ecosystems in dramatic yet uncertain ways.

Description of evidence base

The key message is supported by extensive evidence documented in the Oceans Technical Input Report[102] and additional technical inputs received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter.

Numerous references provide evidence for the increasing acidity (lower pH) of oceans around the world (Ch. 2: Our Changing Climate, Key Message 12).[3,31]

There is a rapid growth in peer-reviewed publications describing how ocean acidification will impact ecosystems,[33,34] but to date evidence is largely based on studies of calcification rather than growth, reproduction, and survival of organisms. For these latter effects, available evidence is from laboratory studies in low pH conditions, rather than in situ observations.[35]

New information and remaining uncertainties

The interplay of environmental stressors may result in "surprises" where the synergistic impacts may be more deleterious or more beneficial than expected. Such synergistic effects create complexities in predicting the outcome of the interplay of stressors on marine ecosystems. Many, but not all, calcifying species are affected by increased acidity in laboratory studies. How those responses will cascade through ecosystems and food webs is still uncertain. Although studies are underway to expand understanding of ocean acidification on all aspects of organismal physiology, much remains to be learned.

Assessment of confidence based on evidence

Confidence is **very high** that carbon dioxide emissions to the atmosphere are causing ocean acidification, and **high** that this will alter marine ecosystems. The nature of those alterations is unclear, however, and predictions of most specific ecosystem changes have **low** confidence at present, but with **medium** confidence for coral reefs.

Key message #3 Traceable Account

Significant habitat loss will continue to occur due to climate change for many species and areas, including Arctic and coral reef ecosystems, while habitat in other areas and for other species will expand. These changes will consequently alter the distribution, abundance, and productivity of many marine species.

Description of evidence base

The key message is supported by extensive evidence documented in the Oceans Technical Input Report[102] and additional technical inputs received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter.

Many peer-reviewed publications[56,70] describe threats to coral reefs induced by global change.

There are also many relevant and recent peer-reviewed publications[53,54,87] that discuss impacts on marine species and resources of habitat change that is induced by climate change.

New information and remaining uncertainties
Regional and local variation is, again, a major component of the remaining uncertainties. Different areas, habitats, and species are responding differently and have very different adaptive capacities. Those species that are motile will certainly respond differently, or at least at a different rate, by changing distribution and migration patterns, compared to species that do not move, such as corals.

Although it is clear that some fish stocks are moving poleward and to deeper water, how far they will move and whether most species will move remains unclear. A key uncertainty is the extent to which various areas will benefit from range expansions of valuable species or increases in productivity, while other areas will suffer as species move away from previously productive areas. The loss of critically important habitat due to climate change will result in changes in species interactions that are difficult to predict.

Assessment of confidence based on evidence
There is **very high** confidence that habitat and ecosystems are changing due to climate change, but that change is not unidirectional by any means. Distribution, abundance, and productivity changes are species and location dependent and may be increasing or decreasing in a complex pattern.

Key message #4 Traceable Account

Rising sea surface temperatures have been linked with increasing levels and ranges of diseases in humans and in marine life, including corals, abalones, oysters, fishes, and marine mammals.

Description of evidence base
The key message is supported by extensive evidence in the Oceans Technical Input Report[102] and additional technical inputs received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter.

As noted in the chapter, the references document increased levels and ranges of disease coincident with rising temperatures.[64,65,66,67]

New information and remaining uncertainties
The interactions among host, environment, and pathogen are complex, which makes it challenging to separate warming due to climate change from other causes of disease outbreaks in the ocean.

Assessment of confidence based on evidence
There is **high** confidence that disease outbreaks and levels are increasing, and that this increase is linked to increasing temperatures. Again, there is substantial local to regional variation but the overall pattern seems consistent.

Key message #5 Traceable Account

Climate changes that result in conditions substantially different from recent history may significantly increase costs to businesses as well as disrupt public access and enjoyment of ocean areas.

Description of evidence base
The key message is supported by extensive evidence documented in the Oceans Technical Input Report[102] and additional technical inputs received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter.

Many peer-reviewed publications describe the predicted impacts of climate change on tourism and recreation industries and their associated infrastructure.[91,92]

New information and remaining uncertainties
Given the complexity of transportation, resource use and extraction, and leisure and tourism activities, there are large uncertainties in impacts in specific locales or for individual activities. Some businesses and communities may be able to adapt rapidly, others less so. Infrastructure impacts of climate change will also be an important part of the ability of businesses, communities, and the public to adapt.

Assessment of confidence based on evidence
As with many other impacts of climate change, the evidence that change is occurring is very strong but the resultant impacts are still uncertain. For all of these human uses, and the associated costs and disruption, the evidence is suggestive and confidence **medium** on the effects of the ongoing changes in ocean conditions.

Key message #6 Traceable Account

In response to observed and projected climate impacts, some existing ocean policies, practices, and management efforts are incorporating climate change impacts. These initiatives can serve as models for other efforts and ultimately enable people and communities to adapt to changing ocean conditions.

Description of evidence base
The key message is supported by extensive evidence documented in the Oceans Technical Input Report[102] and additional technical inputs reports received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter.

Scenarios suggest that adjustments to fish harvest regimes can improve catch stability under increased climate variability. These actions could have a greater effect on biological and economic performance in fisheries than impacts due to warming over the next 25 years.[94]

New information and remaining uncertainties

Efforts are underway 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. While critical knowledge gaps exist, there is a wealth of climate- and ocean-related science pertinent to adaptation.102

Assessment of confidence based on evidence

There is **high** confidence that adaptation planning will help mitigate the impacts of changing ocean conditions. But there is much work to be done to craft local solutions to the set of emerging issues in ocean and coastal areas.