Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II

9 Oceans and Marine Resources

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Recommended Citation for Chapter

Pershing, A.J., R.B. Griffis, E.B. Jewett, C.T. Armstrong, J.F. Bruno, D.S. Busch, A.C. Haynie, S.A. Siedlecki, and D. Tommasi, 2018: Oceans and Marine Resources. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 353–390. doi: 10.7930/NCA4.2018.CH9

On the Web: https://nca2018.globalchange.gov/chapter/oceans

9

Oceans and Marine Resources

Coral reefs in the U.S. Virgin Islands

Key Message 1

Ocean Ecosystems

The Nation's valuable ocean ecosystems are being disrupted by increasing global temperatures through the loss of iconic and highly valued habitats and changes in species composition and food web structure. Ecosystem disruption will intensify as ocean warming, acidification, deoxygenation, and other aspects of climate change increase. In the absence of significant reductions in carbon emissions, transformative impacts on ocean ecosystems cannot be avoided.

Key Message 2

Marine Fisheries

Marine fisheries and fishing communities are at high risk from climate-driven changes in the distribution, timing, and productivity of fishery-related species. Ocean warming, acidification, and deoxygenation are projected to increase these changes in fishery-related species, reduce catches in some areas, and challenge effective management of marine fisheries and protected species. Fisheries management that incorporates climate knowledge can help reduce impacts, promote resilience, and increase the value of marine resources in the face of changing ocean conditions.

Key Message 3

Extreme Events

Marine ecosystems and the coastal communities that depend on them are at risk of significant impacts from extreme events with combinations of very high temperatures, very low oxygen levels, or very acidified conditions. These unusual events are projected to become more common and more severe in the future, and they expose vulnerabilities that can motivate change, including technological innovations to detect, forecast, and mitigate adverse conditions.

Executive Summary

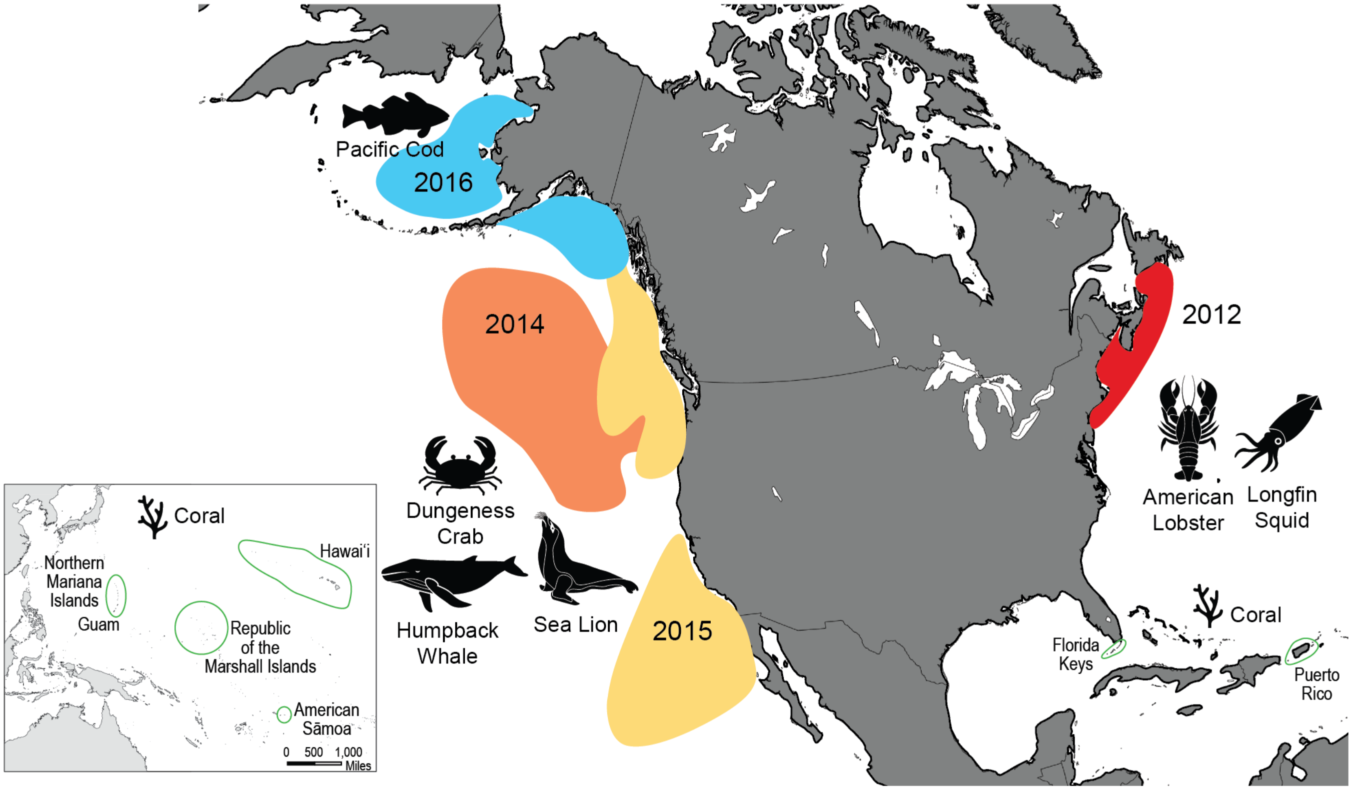
Americans rely on ocean ecosystems for food, jobs, recreation, energy, and other vital services. Increased atmospheric carbon dioxide levels change ocean conditions through three main factors: warming seas, ocean acidification, and deoxygenation. These factors are transforming ocean ecosystems, and these transformations are already impacting the U.S. economy and coastal communities, cultures, and businesses.

While climate-driven ecosystem changes are pervasive in the ocean, the most apparent impacts are occurring in tropical and polar ecosystems, where ocean warming is causing the loss of two vulnerable habitats: coral reef and sea ice ecosystems. The extent of sea ice in the Arctic is decreasing, which represents a direct loss of important habitat for animals like polar bears and ringed seals that use it for hunting, shelter, migration, and reproduction, causing their abundances to decline (Ch. 26: Alaska, KM 1). Warming has led to mass bleaching and/or outbreaks of coral diseases off the coastlines of Puerto Rico, the U.S. Virgin Islands, Florida, Hawai'i, and the U.S.-Affiliated Pacific Islands (Ch. 20: U.S. Caribbean, KM 2; Ch. 27: Hawai'i & Pacific Islands, KM 4) that threaten reef ecosystems and the people who depend on them. The loss of the recreational benefits alone from coral reefs in the United States is expected to reach $140 billion (discounted at 3% in 2015 dollars) by 2100. Reducing greenhouse gas emissions (for example, under RCP4.5) (see the Scenario Products section of App. 3 for more on scenarios) could reduce these cumulative losses by as much as $5.4 billion but will not avoid many ecological and economic impacts.

Ocean warming, acidification, and deoxygenation are leading to changes in productivity, recruitment, survivorship, and, in some cases, active movements of species to track their preferred temperature conditions, with most moving northward or into deeper water with warming oceans. These changes are impacting the distribution and availability of many commercially and recreationally valuable fish and invertebrates. The effects of ocean warming, acidification, and deoxygenation on marine species will interact with fishery management decisions, from seasonal and spatial closures to annual quota setting, allocations, and fish stock rebuilding plans. Accounting for these factors is the cornerstone of climate-ready fishery management. Even without directly accounting for climate effects, precautionary fishery management and better incentives can increase economic benefits and improve resilience.

Short-term changes in weather or ocean circulation can combine with long-term climate trends to produce periods of very unusual ocean conditions that can have significant impacts on coastal communities. Two such events have been particularly well documented: the 2012 marine heat wave in the northwestern Atlantic Ocean and the sequence of warm ocean events between 2014 and 2016 in the northeastern Pacific Ocean, including a large, persistent area of very warm water referred to as the Blob. Ecosystems within these regions experienced very warm conditions (more than 3.6°F [2°C] above the normal range) that persisted for several months or more. Extreme events in the oceans other than those related to temperature, including ocean acidification and low-oxygen events, can lead to significant disruptions to ecosystems and people, but they can also motivate preparedness and adaptation.

Extreme Events in U.S. Waters Since 2012



The 2012 North Atlantic heat wave was concentrated in the Gulf of Maine; however, shorter periods with very warm temperatures extended from Cape Hatteras to Iceland during the summer of 2012. American lobster and longfin squid and their associated fisheries were impacted by the event.[1] The North Pacific event began in 2014[2] and extended toward the shore in 2015[3,4] and into the Gulf of Alaska in 2016,[5,6] leading to a large bloom of toxic algae that impacted the Dungeness crab fishery and contributed directly and indirectly to deaths of sea lions and humpback whales. U.S. coral reefs that experienced moderate to severe bleaching during the 2015–2016 global mass bleaching event[7] are indicated by coral icons. *From Figure 9.3 (Source: Gulf of Maine Research Institute).*

State of the Ocean

From tropical waters in Hawai‘i and Florida, to temperate waters in New England and the Pacific Northwest, to cold Arctic seas off of Alaska, the United States has some of the most diverse and productive ocean ecosystems in the world. Americans rely on ocean ecosystems for food, jobs, recreation, energy, and other vital services, and coastal counties of the United States are home to over 123 million people, or 39% of the U.S. population (Ch. 8: Coastal).[8] The fishing sector alone contributes more than $200 billion in economic activity each year and supports 1.6 million jobs.[9] Coastal ecosystems like coral and oyster reefs, kelp forests, mangroves, and salt marshes provide habitat for many species and shoreline protection from storms, and they have the capacity to sequester carbon.[10,11,12,13]

The oceans play a pivotal role in the global climate system by absorbing and redistributing both heat and carbon dioxide.[14,15] Since the Third National Climate Assessment (NCA3),[16] understanding of the physical, chemical, and biological conditions in the oceans has increased, allowing for improved detection, attribution, and projection of the influence of human-caused carbon emissions on oceans and marine resources.

Human-caused carbon emissions influence ocean ecosystems through three main processes: ocean warming, acidification, and deoxygenation. Warming is the most obvious and well-documented impact of climate change on the ocean. Ocean surface waters have warmed on average 1.3° ± 0.1°F (0.7° ± 0.08°C) per century globally between 1900 and 2016, and more than 90% of the extra heat linked to carbon emissions is contained in the ocean.[15] This warming impacts sea levels, ocean circulation, stratification (density contrast between the surface and deeper waters), productivity, and, ultimately, entire ecosystems. Changes in temperature in the ocean and in the atmosphere alter ocean currents and wind patterns, which influence the seasonality, abundance, and diversity of phytoplankton and zooplankton communities that support ocean food webs.[17,18]

In addition to warming, excess carbon dioxide (CO_2) in the atmosphere has a direct and independent effect on the chemistry of the ocean. When CO_2 dissolves in seawater, it changes three aspects of ocean chemistry.[15,19,20,21] First, it increases dissolved CO_2 and bicarbonate ions, which are used by algae and plants as the fuel for photosynthesis, potentially benefiting many of these species. Second, it increases the concentration of hydrogen ions, acidifying the water. Acidity is measured with the pH scale, with lower values indicating more acidic conditions. Third, it reduces the concentration of carbonate ions. Carbonate is a critical component of calcium carbonate, which is used by many marine organisms to form their shells or skeletons. The saturation state of calcium carbonate is expressed as the term Ω. When the concentration of carbonate ions in ocean water is low enough to yield $\Omega < 1$ (referred to as undersaturated conditions), exposed calcium carbonate structures begin to dissolve. For simplicity, the terms ocean acidification and acidifying will refer to the suite of chemical changes discussed above.

Increased CO_2 levels in the atmosphere are also causing a decline in ocean oxygen concentrations.[15] Deoxygenation is linked to ocean warming through the direct influence of temperature on oxygen solubility (warm water holds less oxygen). Warming of the ocean surface creates an enhanced vertical density contrast, which reduces the transfer of oxygen below the surface. Ecosystem changes related to temperature and stratification further influence oxygen dynamics by altering photosynthesis and respiration.[22,23]

All three of these processes—warming, acidification, and deoxygenation—interact with one another and with other stressors in the ocean environment. For example, nitrogen fertilizer running off the land and entering the Gulf of Mexico through the Mississippi River stimulates algal blooms that eventually decay, creating a large dead zone of water with very low oxygen[24,25] and, simultaneously, low pH.[26] Warmer conditions at the surface slow down the rate at which oxygen is replenished, magnifying the impact of the dead zone. Changes in temperature in the ocean and in the atmosphere affect ocean currents and wind patterns that can alter the dynamics of phytoplankton blooms,[17] which then drive low-oxygen and low-pH events in coastal waters.

Transformations in ocean ecosystems are already impacting the U.S. economy and the coastal communities, cultures, and businesses that depend on ocean ecosystems (Key Message 1). Fisheries provide the most tangible economic benefit of the ocean. While the impact of warming on fish stocks is becoming more severe, there has also been progress in adapting fisheries management to a changing climate (Key Message 2). Finally, the ability for climate-related changes in ocean conditions to impact the United States was made especially clear by major marine heat wave events that occurred along the Northeast Coast in 2012 and along the entire West Coast in 2014–2016 (Key Message 3). During these events, the regions experienced high ocean temperatures similar to the average conditions expected later this century under future climate scenarios. Ecosystem changes included the appearance of warm-water species, increased mortality of marine mammals, and an unprecedented harmful algal bloom, and these factors combined to produce economic stress in some of the Nation's most valuable fisheries.

Key Message 1

Ocean Ecosystems

The Nation's valuable ocean ecosystems are being disrupted by increasing global temperatures through the loss of iconic and highly valued habitats and changes in species composition and food web structure. Ecosystem disruption will intensify as ocean warming, acidification, deoxygenation, and other aspects of climate change increase. In the absence of significant reductions in carbon emissions, transformative impacts on ocean ecosystems cannot be avoided.

Marine species are sensitive to the physical and chemical conditions of the ocean; thus, warming, acidification, deoxygenation, and other climate-related changes can directly affect their physiology and performance.[27,28,29] Differences in how species respond to physical conditions lead to changes in their relative abundance within an ecosystem as species decline or increase in abundance, colonize new locations, or leave places where conditions are no longer favorable.[30,31,32,33] Such reorganization of species in marine communities can result in some species losing resources they depend on for their survival (such as prey or shelter). Other species may be exposed to predators, competitors, and diseases they have rarely encountered before and to which they have not evolved behavioral responses or other defenses.[34,35,36] Climate change is creating communities that are ecologically different from those that currently exist in ocean ecosystems. Reorganization of these communities would change the ecosystem services provided by marine ecosystems in ways that influence regional economies, fisheries harvest, aquaculture, cultural heritage, and shoreline protection (Figure 9.1) (see also Ch. 7: Ecosystems, KM 1; Ch. 8: Coastal, KM 2).[37,38,39,40]

While climate-driven ecosystem changes are pervasive, the most apparent impacts are occurring in tropical and polar ecosystems, where ocean warming is causing the loss of two vulnerable habitats: coral reef and sea ice ecosystems.[41,42] Warming is leading to an increase in coral bleaching events around the globe,[7] and mass bleaching and/or outbreaks of coral diseases have occurred off the coastlines of Puerto Rico, the U.S. Virgin Islands, Florida, Hawai‘i, and the U.S.-Affiliated Pacific Islands.[43,44] Loss of reef-building corals alters the entire reef ecosystem, leading to changes in the communities of fish and invertebrates that inhabit reefs.[45,46] These changes directly impact coastal communities that depend on reefs for food, income, storm protection, and other services (Figure 9.1) (see also Ch. 27: Hawai‘i & Pacific Islands, KM 4).

The extent of sea ice in the Arctic is decreasing, further exacerbating temperature changes and increasing corrosiveness in the Arctic Ocean (Ch. 26: Alaska, KM 1).[15] The decline in sea ice represents a direct loss of important habitat for animals like polar bears and ringed seals that use ice for hunting, shelter, migration, and reproduction, causing their abundances to decline.[47,48,49] The Arctic Ocean food web is fueled by intense blooms of algae that occur at the ice edge. Loss of sea ice is also shifting the location and timing of these blooms, impacting the food web up to fisheries and top predators like killer whales (Ch. 26: Alaska, Figure 26.4).[50,51,52] Surface waters around Alaska have or will soon become permanently undersaturated with respect to calcium carbonate, further stressing these ecosystems (Ch. 26: Alaska, Figure 26.3).

Projected Impacts

The majority of marine ecosystems in the United States and around the world now experience acidified conditions that are entirely different from conditions prior to the industrial revolution (Ch. 7: Ecosystems).[14,53,54] Models estimate that by 2050 under the higher emissions scenario (RCP8.5) (see the Scenario Products section of App. 3 for more on scenarios) most ecosystems (86%) will experience combinations of temperature and pH that have never before been experienced by modern species.[54] Regions of the ocean with low oxygen concentrations are expected to expand and to increasingly impinge on coastal ecosystems.[15,55,56] Warming and ocean acidification pose very high risks for many marine organisms, including seagrasses, warm water corals, pteropods, bivalves, and krill over the next 85 years.[57] Ocean acidification and hypoxia (low oxygen levels) that co-occur in coastal zones will likely pose a greater risk than if species were experiencing either independently.[58] Furthermore, under the higher scenario (RCP8.5), by the end of this century, nearly all coral reefs are projected to be surrounded by acidified seawater that will challenge coral growth.[59]

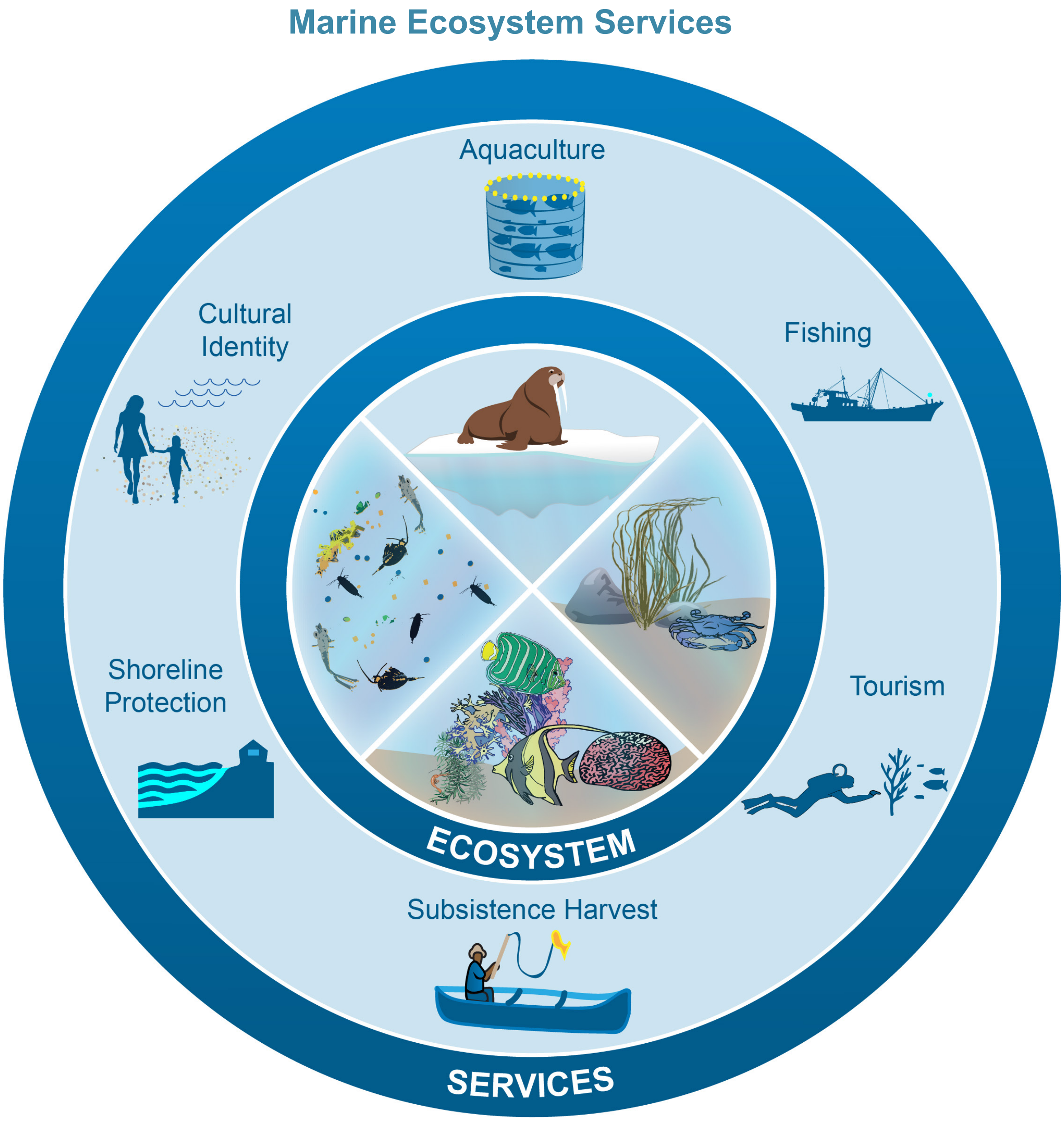


Figure 9.1: The diagram shows some marine ecosystems (center) and the services they provide to human communities (outer ring). Marine ecosystems in the United States range from tropical coral reefs (center bottom) to sea ice ecosystems in the Arctic (center top). They also include ecosystems with freely drifting plankton (center left) and with animals and seaweed that live on the ocean bottom (center right). Climate change is disrupting the structure and function of marine ecosystems in the United States and altering the services they provide to people. These services include food from fishing (commercial, recreational, and subsistence harvest) and aquaculture, economic benefits from tourism, protection of coastal property from storms, and nonmarket goods such as the cultural identity of coastal communities. Source: NOAA.

Changes in biodiversity in the ocean are underway, and over the next few decades will likely transform marine ecosystems.[33] The species diversity of temperate ecosystems is expected to increase as traditional collections of species are replaced by more diverse communities similar to those found in warmer water.[60] Diversity is expected to decline in the warmest ecosystems; for example, one study projects that nearly all existing species will be excluded from tropical reef communities by 2115 under the higher scenario (RCP8.5).[61]

Climate-induced disruption to ocean ecosystems is projected to lead to reductions in important ecosystem services, such as aquaculture and fishery productivity (Key Message 2) and recreational opportunities (Figure 9.1) (Ch. 7: Ecosystems, KM 1). Eelgrass, saltmarsh, and coral reef ecosystems also help protect coastlines from coastal erosion by dissipating the energy in ocean waves (Ch. 8: Coastal, KM 2). The loss of the recreational benefits alone from coral reefs in the United States is expected to reach $140 billion by 2100 (discounted at 3% in 2015 dollars).[62] Reducing greenhouse gas emissions (for example, under RCP4.5) could reduce these cumulative losses by as much as $5.4 billion but will not avoid many ecological and economic impacts.[62]

Opportunities for Reducing Risk

Warming, acidification, and reduced oxygen conditions will interact with other non-climate-related stressors such as pollution or overfishing (Key Message 2). Conservation measures such as efforts to protect older individuals within species,[63,64] maintain healthy fish stocks (Key Message 2),[65] and establish marine protected areas can increase resilience to climate impacts.[66,67,68] However, these approaches are inherently limited, as they do not address the root cause of warming, acidification, or deoxygenation. There is growing evidence that many ecosystem changes can be avoided only with substantial reductions in the global average atmospheric CO_2 concentration.[57,69,70]

Emerging Issues and Research Gaps

Species can adapt or acclimatize to changing physical and chemical conditions, but little is known about species' adaptive capacity and whether the rate of adaptation is fast enough to keep up with the unprecedented rate of change to the environment.[71,72,73] Furthermore, ocean ecosystems are becoming increasingly novel, meaning that knowledge of current ecosystems will be a less reliable guide for future decision-making (Ch. 28: Adaptation, KM 2). Continued monitoring to measure the effects of warming, acidification, and deoxygenation on marine ecosystems, combined with laboratory and field experiments to understand the mechanisms of change, will enable improved projections of future change and identification of effective conservation strategies for changing ocean ecosystems.

Key Message 2

Marine Fisheries

Marine fisheries and fishing communities are at high risk from climate-driven changes in the distribution, timing, and productivity of fishery-related species. Ocean warming, acidification, and deoxygenation are projected to increase these changes in fishery-related species, reduce catches in some areas, and challenge effective management of marine fisheries and protected species. Fisheries management that incorporates climate knowledge can help reduce impacts, promote resilience, and increase the value of marine resources in the face of changing ocean conditions.

Variability in ocean conditions can have significant impacts on the distribution and productivity (growth, survival, and reproductive success) of fisheries species.[74,75] For stocks near the warm end of their range (such as cod in the Gulf of Maine),[76] increases in temperature generally lead to productivity declines; in contrast, warming can enhance the productivity of stocks at the cold end of their range (such as Atlantic croaker).[77] These changes in productivity have direct economic and social impacts. For example, warming water temperatures in the Gulf of Maine exacerbated overfishing of Gulf of Maine cod, and the subsequent low quotas have resulted in socioeconomic stress in New England.[76] Reductions in the abundance of Pacific cod associated with the recent heat wave in the Gulf of Alaska led to an inability of the fishery to harvest the Pacific cod quota in 2016 and 2017, and to an approximately 80% reduction in the allowable quota in 2018.[78]

Changes in productivity, recruitment, survivorship, and, in some cases, active movements of target species to track their preferred temperature conditions are leading to shifts in the distribution of many commercially and recreationally valuable fish and invertebrates, with most moving poleward or into deeper water with warming oceans.[31,79,80,81,82] Shifts in fish stock distributions can have significant implications for fisheries management, fisheries, and fishing-dependent communities. Fishers may be expected to move with their target species; however, fishing costs, port locations, regulations, and other factors can constrain the ability of the fishing industry to closely track changes in the ocean.[83] Shifts across governance boundaries are already creating management challenges in some regions and can become trans-boundary issues for fish stocks near national borders (Ch. 16: International, KM 4).[84]

Changes in the timing of seasonal biological events can also impact the timing and location of fisheries activities. The timing of peak phytoplankton and zooplankton biomass is influenced by oceanographic conditions (such as stratification and temperature).[85,86] Since juvenile fish survival and growth are dependent on food availability, variability in the timing of plankton blooms affects fish productivity (e.g., Malick et al. 2015[87]). Migration and spawning, events that often depend on temperature conditions, are also changing.[1,88,89,90] For example, management of the Chesapeake Bay striped bass fishery is based on a fixed fishing season that is meant to avoid catching large egg-bearing females migrating early in the season. As temperatures rise, more females will spawn early in the season, reducing their availability to fishers.[89] The location and size of coastal hypoxic zones (which are likely exacerbated by temperature and ocean acidification)[56] can affect the spatial dynamics of fisheries, such as the Gulf of Mexico shrimp fishery, with potential economic repercussions.[91]

Projected Impacts

The productivity, distribution, and phenology of fisheries species will continue to change as oceans warm and acidify. These changes will challenge the ability of existing U.S. and international frameworks to effectively manage fisheries resources and will have a variety of impacts on fisheries and fishing-dependent sectors and communities. Projected increases in ocean temperature are expected to lead to declines in maximum catch potential under a higher scenario (RCP8.5) in all U.S. regions except Alaska (Figure 9.2).[92] Because tropical regions are already some of the warmest, there are few species available to replace species that move to cooler water.[61] This means that fishing communities in Hawai‘i and the Pacific Islands, the Caribbean, and the Gulf of Mexico are particularly vulnerable to climate-driven changes in fish populations. Declines of 10%–47% in fish catch potential in these warm regions, as compared to the 1950–1969 level, are expected with a 6.3°F (3.5°C) increase in global atmospheric surface temperature relative to preindustrial levels (reached by 2085 under RCP8.5).[92] In contrast, total fish catch potential in the Gulf of Alaska is projected to increase by approximately 10%, while Bering Sea catch potential may increase by 46%.[92] However, species-specific work suggests that catches of Bering Sea pollock, one of the largest fisheries in the United States, are expected to decline,[93] although price increases may mitigate some of the economic impacts.[94] Similarly, abundance of the most valuable fishery in the United States, American lobster, is projected to decline under RCP8.5.[64] Ocean acidification is expected to reduce harvests of U.S. shellfish, such as the Atlantic sea scallop;[95] while future work will better refine impacts, cumulative consumer losses of $230 million (in 2015 dollars) across all U.S. shellfish fisheries are anticipated by 2099 under the higher scenario (RCP8.5).[62]

The implications of the projected changes in fisheries dynamics on revenue[94,96] and small-scale Indigenous fisheries remain uncertain.[97] Indigenous peoples depend on salmon and other fishery resources for both food and cultural value, and reductions in these species would pose significant challenges to some communities (e.g., Krueger and Zimmerman 2009[98]) (Ch. 15: Tribes, KM 2; Ch. 24: Northwest). Additionally, western Alaska communities receive a significant share of the revenues generated by Alaska groundfish fisheries through the Western Alaska

Projected Changes in Maximum Fish Catch Potential

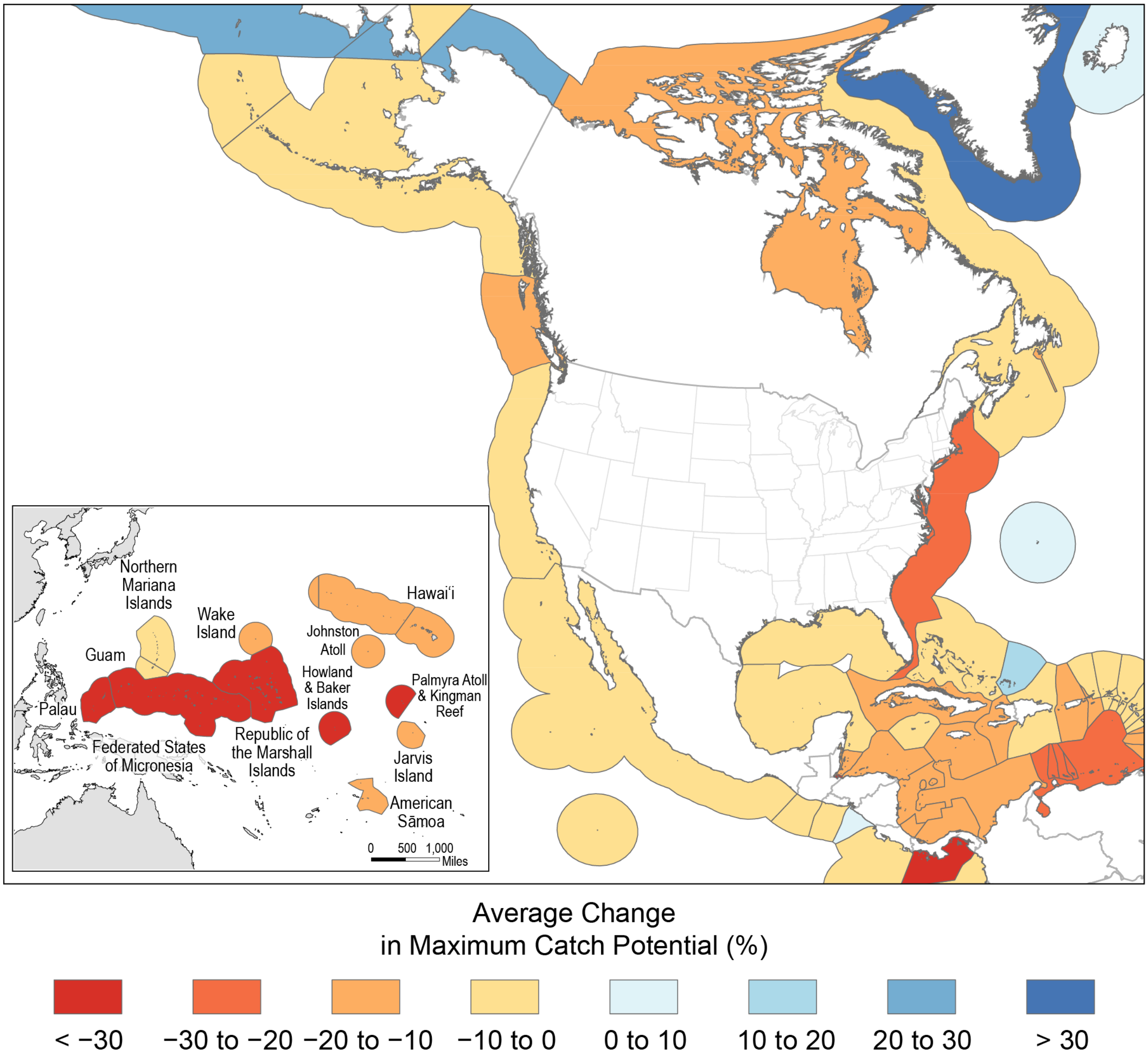


Figure 9.2: The figure shows average projected changes in fishery catches within large marine ecosystems for 2041–2060 relative to 1991–2010 under a higher scenario (RCP8.5). All U.S. large marine ecosystems, with the exception of the Alaska Arctic, are expected to see declining fishery catches. Source: adapted from Lam et al. 2016.[96]

Community Development Quota program.[99] This program provides an important source of fishery-derived income for these communities. Where there is strong reliance of fish stocks on specific habitats, shifts may lead to fish becoming more concentrated when water temperature or other changes in ocean conditions push species against a physical boundary such as ice or the ocean bottom.[83] Alternatively, shifts in species distributions are likely to drive vessels farther from port, increasing fishing costs and potentially impacting vessel safety.[100] Under such conditions, there will also be new opportunities that result from species becoming more abundant or spatially available. Advance knowledge and projections of anticipated changes allow seafood producers to develop new markets and harvesters the ability to adapt their gear and fishing behavior to take advantage of new opportunities.[84,101,102]

Opportunities for Reducing Risk

A substantial reduction of greenhouse gas emissions would reduce climate-driven ocean changes and significantly reduce risk to fisheries.[103] Warming, acidification, and deoxygenation interact with fishery management decisions, from seasonal and spatial closures to annual quota setting, allocations, and fish stock rebuilding plans. Accounting for these factors is the cornerstone of climate-ready fishery management.[84,104,105] Modeling studies show that climate-ready, ecosystem-based fisheries management can help reduce the impacts of some anticipated changes and increase resilience under changing conditions.[93,106,107] There is now a national strategy for integrating climate information into fishery decision-making,[105] and the North Pacific Fishery Management Council is now directly incorporating ocean conditions and climate projections in its planning and decision-making.[108,109]

National and regional efforts have been underway to characterize community vulnerability to climate change and ocean acidification.[38,110,111] The development of climate-ready fisheries will be particularly important for coastal communities, especially those that are highly dependent on fish stocks for food and for income. Targeting and participating in an increased diversity of fisheries with more species can improve economic resilience of harvesters and fishing communities.[112,113,114] Current policies can create barriers that impede diversification,[112] but more dynamic management can enable better adaptation.[115] Even without directly accounting for climate effects, precautionary fishery management and better incentives can increase economic benefits and improve resilience.[64,65,116]

Emerging Issues and Research Gaps

Many studies have documented the impact of temperature on fish distribution and productivity, enabling initial projections of species distribution, productivity, and fishery catch potential under future warming (e.g., Cheung 2016[103]). While laboratory studies have shown that ocean acidification can impact fish and their prey,[117] there have been no studies demonstrating that acidification is currently limiting the productivity of wild fish stocks. Acidification will become an increasingly important driver of ocean ecosystem change.[39] It is likely that the primarily temperature-based projections described above are underestimating the total magnitude of future changes in fisheries. More work would be required to understand how management and climate change are likely to interact.[105,118] Climate vulnerability assessments (e.g., Hare et al.[119]) estimate which fisheries are most vulnerable in a changing climate and could be used to develop adaptation strategies and prioritize research efforts.

Key Message 3

Extreme Events

Marine ecosystems and the coastal communities that depend on them are at risk of significant impacts from extreme events with combinations of very high temperatures, very low oxygen levels, or very acidified conditions. These unusual events are projected to become more common and more severe in the future, and they expose vulnerabilities that can motivate change, including technological innovations to detect, forecast, and mitigate adverse conditions.

The first two Key Messages focused on the impacts of long-term climate trends. Ocean conditions also vary on a range of timescales, with month-to-month and year-to-year changes aligning with many biological processes in the ocean. The interaction between long-term climate change and shorter-term variations creates the potential for extreme conditions—abrupt increases in temperature, acidity, or deoxygenation (Figure 9.3). Recent extreme events in U.S. waters demonstrated that these events can be highly disruptive to marine ecosystems and to the communities that depend on them. Furthermore, these events provide a window into the conditions and challenges likely to become the norm in the future.

Extreme Events in U.S. Waters Since 2012

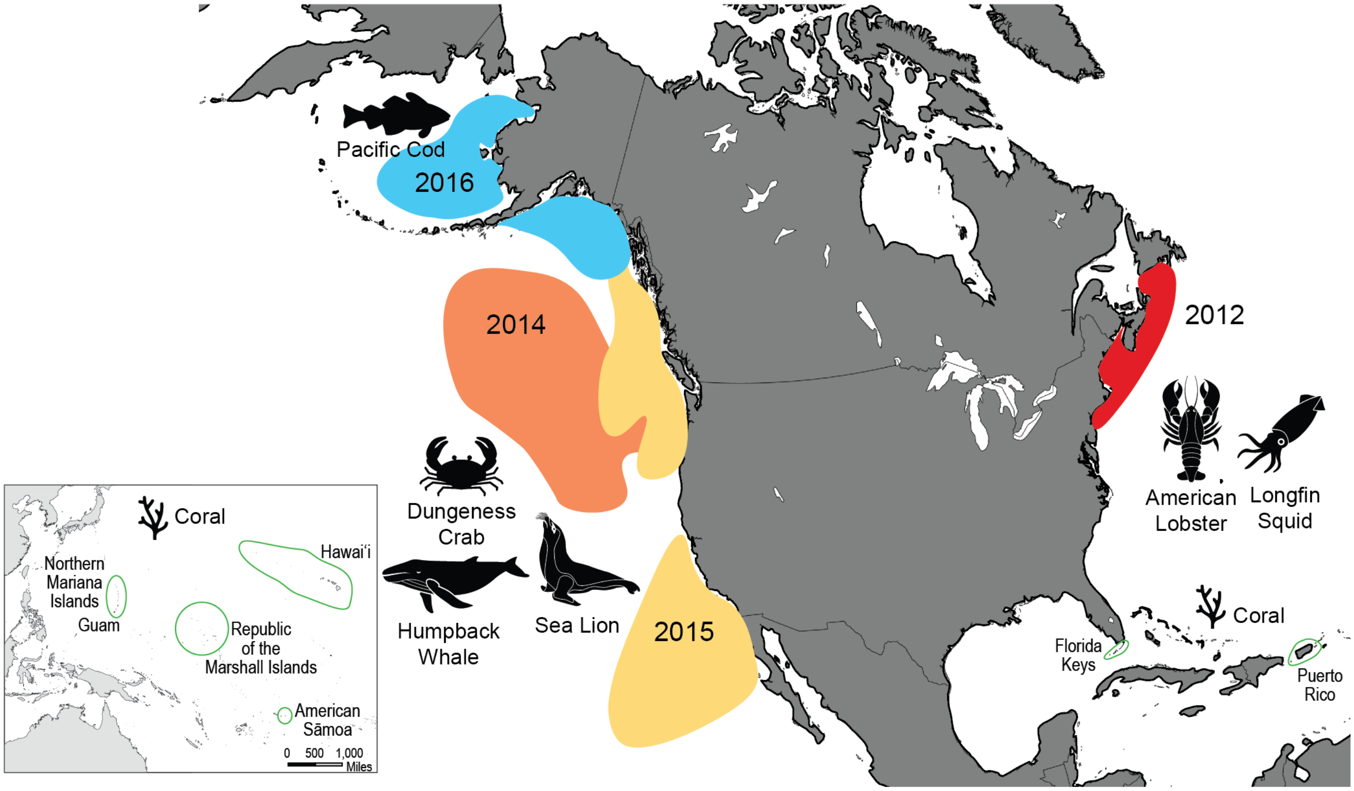


Figure 9.3: The 2012 North Atlantic heat wave was concentrated in the Gulf of Maine; however, shorter periods with very warm temperatures extended from Cape Hatteras to Iceland during the summer of 2012. American lobster and longfin squid and their associated fisheries were impacted by the event.[1] The North Pacific event began in 2014[2] and extended into shore in 2015[3,4] and into the Gulf of Alaska in 2016,[5,6] leading to a large bloom of toxic algae that impacted the Dungeness crab fishery and contributed directly and indirectly to deaths of sea lions and humpback whales. U.S. coral reefs that experienced moderate to severe bleaching during the 2015–2016 global mass bleaching event[7] are indicated by coral icons. Source: Gulf of Maine Research Institute.

Two recent events have been particularly well documented: the 2012 marine heat wave in the northwestern Atlantic Ocean (Ch. 18: Northeast, Box 18.1) and an event occurring between 2014 and 2016 in the northeastern Pacific Ocean, nicknamed the Blob (Figure 9.3) (Ch. 24: Northwest, KM 1; Ch. 25: Southwest, KM 3; Ch. 26: Alaska, KM 1). Ecosystems within these regions experienced very warm conditions (greater than 3.6°F [2°C] above the normal range) that persisted for several months or more.[1,2,3] Additionally, the very warm temperatures during the 2015–2016 El Niño led to widespread coral bleaching, including reefs off of American Sāmoa, the Marianas, Guam, Hawai‘i, Florida, and Puerto Rico (Ch. 20: U.S. Caribbean, KM 2; Ch. 27: Hawai‘i & Pacific Islands, KM 4).[7]

Coastal communities are especially susceptible to changes in the marine environment,[110,111] and the interaction between people and the ecosystem can amplify the impacts and increase the potential for surprises (Ch. 17: Complex Systems, KM 1). In the Gulf of Maine in 2012, warm temperatures caused lobster catches to peak 3–4 weeks earlier than usual. The supply chain was not prepared for the early influx of lobsters, leading to a severe drop in price.[1] The North Pacific event, centered in 2015, featured an extensive bloom of the toxic algae *Pseudo-nitzschia*[4,120] that led to mass mortalities of sea lions and whales and the closure of the Dungeness crab fishery.[121,122] The crab fishery then reopened in the spring of 2016, normally a time when fishing effort is low. The shift in timing led to increased fishing activity during the spring migration of humpback and gray whales and thus an elevated incidence of whales becoming entangled in crab fishing gear.[122] Continued warm temperatures in the Gulf of Alaska during 2016[5] led to reduced catch of Pacific cod.[78]

Extreme events other than those related to temperature can also occur in the oceans. Short-term periods of low-oxygen, low-pH (acidified) waters have occurred more frequently along the Pacific coast during intense upwelling events.[15,123,124,125,126] The acidified waters were corrosive ($\Omega < 1$) and reduced the survival of larval Pacific oysters (*Crassostrea gigas*) in commercial hatcheries that support oyster aquaculture[127,128] and increased dissolution of the shells of pteropods, a type of planktonic snail important in many ocean ecosystems.[129,130,131,132]

Projected Impacts

The extreme temperatures experienced during both recent heat waves exposed ecosystems to conditions not expected for 50 or more years into the future, providing a window into how future warming may impact these ecosystems. In both regions, southerly species moved northward, and warmer conditions in the spring shifted the timing of biological events earlier in the year.[1,133]

In the future, the same natural patterns of climate variability associated with the heat waves in both ocean basins[3,134,135,136,137] will continue to occur on top of changing trends in average conditions, leading to more extreme events relative to current averages.[138]

Human-caused climate change likely already contributed to the events observed in 2012 and 2015, helping drive temperatures to record levels.[139,140] Ocean acidification events such as those described along the Pacific coast are already increasing and are projected to become more intense, longer, and increasingly common.[53,141] The increase in intensity and frequency of toxic algal blooms has been linked to warm events and increasing temperatures in both the Atlantic and Pacific Oceans.[4,120,142]

Changes resulting from human activities, especially increased nutrient loads, accelerate the development of hypoxic events in many areas of the world's coastal ocean.[15,143]

Opportunities for Reducing Risk

Extreme events in the oceans can lead to significant disruptions to ecosystems and people, but they can also drive technological adaptation. Several corrosive events along the Pacific Northwest coast prompted the Pacific Coast Shellfish Growers Association to work with scientists to test new observing instruments and develop management procedures.[128] The hatcheries now monitor pH and pCO_2 (partial pressure of carbon dioxide) in real time and adjust seawater intake to reduce acidity. Similar practices are being employed on the East Coast to adapt shellfish hatcheries to the increasing frequency of low-pH events associated with increased precipitation and runoff.[144]

Similarly, the need to forecast El Niño events led to the development of seasonal climate forecast systems.[145] Current modeling systems make it possible to forecast temperature, pH, and oxygen conditions several months into the future.[101,102,146,147,148] Operational forecasts are also being developed for harmful algal blooms[149] and for the timing of Maine's lobster fishery.[150] Further engagement with users would improve the utility of these emerging forecasts.[101,148]

Emerging Issues and Research Gaps

The recent extreme events in U.S. ocean waters were the result of the interaction between natural cycles and long-term climate trends. As carbon emissions drive average temperatures higher and increase ocean acidification, natural climate cycles will occur on top of ocean conditions that are warmer, acidified, and have generally lower oxygen levels. A major uncertainty is whether these natural cycles will function in the same way in an altered climate. For example, the natural patterns of climate variability that contributed to the formation of the Blob show increasing variability in climate model projections.[3] This suggests that similar temperature events in the North Pacific may be more likely. Unusually persistent periods of warm weather led to the formation of both the North Atlantic and North Pacific heat waves.[2,134,151] Observational and modeling studies suggest that the loss of Arctic sea ice may disrupt mid-latitude atmospheric circulation patterns, making extreme weather conditions more likely (e.g., Overland et al. 2016, Vavrus et al. 2017, but see Cohen 2016[152,153,154]). This mechanism suggests that extremes in the ocean may be more extreme in the future, even after accounting for climate trends.

Conclusion

Ocean ecosystems provide economic, recreational, and cultural opportunities for all Americans. Increasing temperatures, ocean acidification, and deoxygenation are likely to alter marine ecosystems and the important benefits and services they provide. There has been progress in developing management strategies and technological improvements that can improve resilience in the face of long-term changes and abrupt events. However, many impacts, including losses of unique coral reef and sea ice ecosystems, can only be avoided by reducing carbon dioxide emissions.

Acknowledgments

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Opening Image Credit

Coral reefs: NOAA Coral Reef Conservation Program.

Traceable Accounts

Process Description

The goal when building the writing team for the Oceans and Marine Resources chapter was to assemble a group of scientists who have experience across the range of marine ecosystems (such as coral reefs and temperate fisheries) that are important to the United States and with expertise on the main drivers of ocean ecosystem change (temperature, deoxygenation, and acidification). We also sought geographic balance and wanted a team that included early-career and senior scientists.

We provided two main opportunities for stakeholders to provide guidance for our chapter. This included a town hall meeting at the annual meeting of the Association for the Sciences of Limnology and Oceanography and a broadly advertised webinar hosted by the National Oceanic and Atmospheric Administration. Participants included academic and government scientists, as well as members of the fisheries and coastal resource management communities. We also set up a website to collect feedback from people who were not able to participate in the town hall or the webinar.

An important consideration in our chapter was what topics we would cover and at what depth. We also worked closely with the authors of Chapter 8: Coastal to decide which processes and ecosystems to include in which chapter. This led to their decision to focus on the climate-related physical changes coming from the ocean, especially sea level rise, while our chapter focused on marine resources, including intertidal ecosystems such as salt marshes. We also decided that an important goal of our chapter was to make the case that changing ocean conditions have a broad impact on the people of the United States. This led to an emphasis on ecosystem services, notably fisheries and tourism, which are easier to quantify in terms of economic impacts.

Key Message 1

Ocean Ecosystems

The Nation's valuable ocean ecosystems are being disrupted by increasing global temperatures through the loss of iconic and highly valued habitats and changes in species composition and food web structure (*very high confidence*). Ecosystem disruption will intensify as ocean warming, acidification, deoxygenation, and other aspects of climate change increase (*very likely, very high confidence*). In the absence of significant reductions in carbon emissions, transformative impacts on ocean ecosystems cannot be avoided (*very high confidence*).

Description of evidence base

Ocean warming has already impacted biogenically built habitats. Declines in mussel beds, kelp forests, mangroves, and seagrass beds, which provide habitat for many other species, have been linked to ocean warming and interactions of warming with changes in oxygen levels or other stressors (see Ch. 27: Hawai'i & Pacific Islands, Key Message 4 for impacts on mangrove systems in the Pacific Islands).[155,156,157,158] Sea level rise will continue to reduce the extent of many estuarine and coastal habitats (for example, salt marshes, seagrass beds, and shallow coral reefs) in locations where they fail to accrete quickly enough to outpace rising seas.[159,160] The composition and timing of phytoplankton blooms are shifting, and dominant algal species are changing, which can cause bottom-up changes in food web structure.[17,18,161]

Some of the most apparent ecosystem changes are occurring in the warmest and coldest ocean environments, in coral reef and sea ice ecosystems. Live coral cover in coral reef ecosystems around the world has declined from a baseline of about 50%–75% to only 15%–20% (the current average for most regions; see Bruno & Valdivia 2016; Eddy et al. 2018[69,162]), primarily due to ocean warming.[163,164] Exposure to water temperatures just a few degrees warmer than normal for a given reef can cause corals to bleach; bleached corals have expelled their colorful symbiotic dinoflagellate algae, and the lack of algae can partially or wholly kill coral colonies.[165] Over the past four decades, warming has caused annual average Arctic sea ice extent to decrease between 3.5% and 4.1% per decade; sea ice melting now begins at least 15 days earlier than it did historically (Ch. 26: Alaska, KM 1).[166,167,168] Several studies have shown that sea ice loss has changed food web dynamics, caused diet shifts, and contributed to a continued decline of some Arctic seabird and mammal populations.[49,169,170,171,172] For instance, polar bear litter sizes have already declined and are projected to decline further; models suggest that sea ice breaking up two months earlier than the historical normal will decrease polar bear pregnancy success in Huntington Bay by 55%–100%.[173,174]

Species differ in their response to warming, acidification, and deoxygenation. This imbalance in sensitivity will lead to ecosystem reorganization, as confirmed by a number of recent ecosystem models focused on phytoplankton[17,175,176] and on entire food webs.[40,68,177,178,179,180] Local extinction and range shifts of marine species due to changes in environmental conditions have already been well documented, as have the corresponding effects on community structure.[32,81]

Global-scale coral bleaching events in 1987, 1998, 2005, and 2015–2016 have caused a rapid and dramatic reduction of living coral cover; as the regularity of these events increases, their effects on ecosystem integrity may also increase.[7,164,181,182] Warming increases the likelihood of coral disease outbreaks and reduces coral calcification, reproductive output, and a number of other biological processes related to fitness.[183,184] Under the higher scenario (RCP8.5), all shallow tropical coral reefs will be surrounded by water with $\Omega < 3$ by the end of this century.[59] Laboratory research finds that many coral species are negatively impacted by exposure to high CO_2 conditions,[185,186,187] and field research conducted near geologic CO_2 vents have found that exposure to high CO_2 conditions changes some, but not all, coral communities.[188,189,190,191] Sea ice loss in the Arctic is expected to continue through this century, very likely resulting in nearly sea ice-free late summers by the middle of the century (Ch. 26: Alaska, KM 1).[166] Ice-free summers will result in the loss of habitats in, on, and under the ice and the emergence of a novel ecosystem in the Arctic.[51] Arctic waters are also acidifying faster than expected, in part due to sea ice loss.[192]

Conservation measures, such as ecosystem-based fisheries management (Key Message 2) and marine-protected areas that reduce or respond to these other stressors, can increase resilience;[66,67] however, these approaches have limits and can only slow the impact of climate change and ocean acidification.[68] Ocean warming, acidification, and deoxygenation, among other indirect stressors, will lead to alterations in species distribution, the decline of some species' calcification, and mismatched timing of prey–predator abundance that cannot be fully avoided with management strategies.[33,193] Coral bleaching occurs on remote reefs, suggesting that even pristine reefs will be impacted in a warmer, more acidified ocean.[69,70] Without substantial reductions in CO_2

emissions, massive and sometimes irreversible impacts are very likely to occur in marine ecosystems, including those vital to coastal communities.[57]

Major uncertainties

Further research is necessary to fully understand how multiple stressors, such as temperature, ocean acidification, and deoxygenation, will concurrently alter marine ecosystems in U.S. waters. More research on the interaction of multiple stressors and in scaling results from individual to population or community levels is needed.[27,194,195,196]

Most species have some capacity to acclimate to changes in thermal and chemical conditions, depending on the rate and magnitude at which conditions change, and there may be enough genetic variation in some populations to allow for evolution.[73,197,198,199] Some research suggests that only microbes have the ability to acclimate to the expected anthropogenic temperature and pH changes, suggesting a reduction in the diversity and abundance of key species and a change in trophic energy transfer, which underpin ecosystem function of the modern ocean.[33]

Description of confidence and likelihood

The amount of research and agreement among laboratory results, field observations, and model projections demonstrate *very high confidence* that ecosystem disruption has occurred due to climate change, particularly in tropical coral reef and sea ice-associated ecosystems due to the global increase of ocean temperatures. It is *very likely* that ecosystem disruption will intensify later this century under continued carbon emissions, as there is *very high confidence* that warming, acidification, deoxygenation, and other aspects of climate change will accelerate. While conservation and management practices can build resilience in some ecosystems, there is *very high confidence* that only reductions in carbon emissions can avoid significant ecosystem disruption, especially in coral reef and sea ice ecosystems.

Key Message 2

Marine Fisheries

Marine fisheries and fishing communities are at high risk from climate-driven changes in the distribution, timing, and productivity of fishery-related species (*likely, high confidence*). Ocean warming, acidification, and deoxygenation are projected to increase these changes in fishery-related species, reduce catches in some areas, and challenge effective management of marine fisheries and protected species (warming: *very likely, very high confidence;* acidification and deoxygenation: *likely, high confidence*). Fisheries management that incorporates climate knowledge can help reduce impacts, promote resilience, and increase the value of marine resources in the face of changing ocean conditions.

Description of evidence base

Most evidence of the impacts of climate variability on U.S. living marine resources comes from numerous studies examining the response of these species to variability in ocean temperature. There is strong evidence that fluctuations in ocean temperature, either directly or indirectly via impacts to food web structure, are associated with changes in the distribution,[31,79,80,81] productivity,[74,75,76,77,200,201,202] and timing of key life-history events, such as the spawning[1,31,88,89] of fish and invertebrates in U.S. waters. These temperature-driven changes in the dynamics of living marine resources in turn affect commercial fisheries catch quantity,[79] composition,[203] and fisher behavior.[1,83,204,205] Beyond temperature, there is robust evidence from experimental studies demonstrating the impacts of oxygen and pH variability on the productivity of marine fish and invertebrates.[55,117,206] However, studies linking changes in oxygen or pH to variations in fisheries and aquaculture dynamics in the field are few and are mainly regional and/or specific to localized deoxygenation or acidification events.[71,128,207]

These observational and experimental studies have provided the foundation for the development of models projecting future impacts of changing climate and ocean conditions on fisheries. Global and regional applications of such models provide strong evidence that changes in future ocean warming will alter fisheries catches in U.S. waters.[64,100,103,208,209,210] The projected decrease in catch potential in the tropics and the projected increase in high-latitude regions under both RCP4.5 and RCP8.5 scenarios are robust to model structural uncertainty[103] and are consistent across modeling approaches.[100,103,209,210] In addition, there is moderate evidence from regional ecosystem and single-species models of reduced future catch in specific U.S. regions from future ocean acidification.[40,95,177,179,211]

Fisheries management in the United States has become increasingly effective at setting sustainable harvest levels, and the number of U.S. fisheries that are overfished or subjected to overfishing has declined in most regions.[212] Science-informed management in general has been shown to be effective in improving ecosystem status[107] and has been projected to greatly improve the benefits from marine resources.[65] Climate change presents new challenges to management systems, as some species move across management boundaries and away from traditional fishing grounds and as productivity patterns shift. Management approaches that do not consider climate-driven ecosystem changes can lead to overfishing when the environment shifts rapidly.[76,213] Some measures have been proposed to make the fisheries management system more climate ready.[84,105,214] In many cases, these management strategies will include measures to allow for greater flexibility for harvesters to adapt to changing distributions and quantities of target species. Some preliminary evidence suggests that the use of climate-informed harvest rules can improve fishery sustainability in a variable environment,[102] but at present, few fisheries management decisions integrate climate-related environmental information.[215] The North Pacific Fishery Management Council is currently examining a strategic, multispecies, climate-enhanced model that informs managers how climate change and variation are expected to impact key stocks.[106]

Major uncertainties

While shifts in the productivity and distribution of living marine resources and ecosystem structure are expected to change catch potential and catch composition in U.S. regions, many uncertainties exist. Projections of catch potential have largely been performed using dynamical bioclimatic envelope models (e.g., Cheung et al.[103]). In these models, the spatial population dynamics of fish stocks are forced by temperature (with additional net primary productivity effects on carrying capacity and pH and oxygen effects on growth) and do not include the potential for major changes in species interactions, as has previously occurred with warming events (e.g., Vergés et al.[32]) and food web structure (e.g., Fay et al.[179]). Furthermore, recent studies indicate that zooplankton and export production may serve as better indicators of carrying capacity for fisheries than net primary productivity.[210,216] Net primary productivity trends will likely be amplified by higher trophic levels, such as zooplankton and ultimately fish; thus, trends in catch potential projected from primary productivity alone may underestimate future changes.[210] These models also do not consider the potential for evolutionary adaptation of marine species. Uncertainties in projections are particularly high for primary productivity, oxygen, and pH, especially at regional and coastal scales,[217,218,219] but these uncertainties are not typically incorporated into projected catch trends. In terms of the economic impacts on consumers, there is also uncertainty about how potential decreases in the catch of some species will impact net revenues, as lower quantities will be compensated in some cases by increased prices paid by consumers (e.g., Seung and Ianelli[94]). Fish prices are expected to increase very modestly over the next decade, yet there are great uncertainties in longer-term prices based on uncertainty about climate, economic growth, and the effectiveness of management in fisheries around the world.[220]

In addition, climate change is only one of many stressors affecting fish dynamics. Future fish distribution, abundance, and productivity will depend on the interaction between these stressors, including fishing and climate-related stressors. Conceptually and empirically, it is clear that fishers are responding to a wide diversity of factors and may not narrowly follow shifting fish populations.[83,221,222] The development of management measures that respond rapidly to dramatic shifts in environmental factors that impact recruitment, productivity, and distribution will also reduce the potential impacts of climate change by avoiding overfishing in times of environmental stress.

Description of confidence and likelihood

There is *high confidence* that climate change-driven alterations in the distribution, timing, and productivity of fishery-related species will *likely* lead to increased risk to the Nation's valuable marine fisheries and fishing communities. There is *very high confidence* that future ocean warming will *very likely* increase these changes in fishery-related species, reduce catches in some areas, and challenge effective management of marine resources. There is *high confidence* that ocean acidification and deoxygenation will *likely* reduce catches in some areas, which will challenge effective management of marine fisheries and protected species.

Key Message 3

Extreme Events

Marine ecosystems and the coastal communities that depend on them are at risk of significant impacts from extreme events with combinations of very high temperatures, very low oxygen levels, or very acidified conditions. These unusual events are projected to become more common and more severe in the future (*very likely, very high confidence*), and they expose vulnerabilities that can motivate change, including technological innovations to detect, forecast, and mitigate adverse conditions.

Description of evidence base

Marine heat waves have been described as regions of large-scale and persistent positive sea surface temperature anomalies that can vary in size, distribution, timing, and intensity akin to their terrestrial counterparts.[137,223] Well-documented marine heat waves have recently occurred in the northwest Atlantic in 2012[1,134,151] and the North Pacific in 2014–2016.[2,6]

Each of these events resulted in documented impacts to ecosystems and, in many cases, to the human communities to which they were connected. The recent major events in the U.S. northwest Atlantic and North Pacific led to economic challenges in the American lobster, Dungeness crab, and Gulf of Alaska Pacific cod fisheries.[1,2,78,224]

Abrupt warming can induce other ecosystem-level impacts. The North Pacific event featured an extensive bloom of the harmful algae *Pseudo-nitzschia*[4,120] that led to mass mortalities of sea lions and whales and the closure of the Dungeness crab fishery. The increase in intensity and occurrence of these toxic algal blooms has been linked to warm events in both the Atlantic and the Pacific.[4,120,142] Abrupt warming was inferred to trigger the expansion of the North Pacific oxygen minimum zone through reduced oxygen solubility and increased marine productivity.[225]

Extreme events with corrosive ($\Omega < 1$) and/or low oxygen conditions can occur when deep waters, which are generally corrosive and have low oxygen levels, are brought into the coastal area during upwelling. They can also occur in response to the delivery of corrosive freshwater from the landscape, ice melting, and storms. These conditions now occur more frequently in coastal waters of the Pacific coast of the United States.[39,126,131,226,227,228,229,230,231] Such events have led to the elevated mortality of coastal shellfish in hatcheries[128] and die-offs of crabs and other animals living on the ocean bottom.[123]

Heat wave, high-acidity, and low-oxygen events are all produced by variability in the system occurring on timescales ranging from days to years. For example, recent marine heat waves have been linked to natural climate modes such as the North Atlantic Oscillation, Atlantic Multidecadal Oscillation, Pacific Decadal Oscillation, or North Pacific Gyre Oscillation, which change over several years.[3,137] Persistent weather patterns lasting several months can further amplify conditions in the ocean, leading to extreme conditions.[2,134,151] These climate modes and atmospheric conditions occur on top of the long-term trends caused by global climate change. Thus, as climate change progresses, events with temperatures above a certain level, oxygen below a certain level, or pH below a specified level will occur more frequently and will last longer.[56,141,146,232]

The intensity of corrosive events along the upwelling margin of the Pacific coast of the United States is increasing due to more intense winds over the past decade and ocean acidification.[15,53,123,125] In Alaska waters, these events are associated with freshwater inputs and storm events that may also have a link to climate change.[226,227,228,229,230,233]

There is ample evidence that extreme events motivate adaptive change in human systems. For example, Hurricane Katrina and Superstorm Sandy motivated communities near the affected areas to expand planning against future storms.[234,235] The 2012 North Atlantic heat wave prompted the development of a forecast system to help Maine's lobster fishery avoid future supply chain disruptions (Ch. 18: Northeast).[150] The impact of corrosive waters on shellfish hatcheries in the Pacific Northwest motivated the development of new technology to monitor and manage water chemistry in shellfish hatcheries.[128]

Major uncertainties

The description above assumes that natural modes of climate variability remain the same and can be simply added to baseline conditions set by the global climate. There is evidence that some natural climate modes may change in the future. As mentioned in the narrative, the climate oscillations linked to the 2014–2016 event in the North Pacific increase in amplitude in climate model projections.[3,135,236] This suggests that extreme events will be more likely in the future, even without accounting for the shift to a warmer temperature baseline. Declines in Arctic sea ice are also hypothesized to impact future climate variability by causing the atmospheric jet stream to get stuck in place for days and weeks (e.g., Overland et al. 2016, Vavrus et al. 2017, but see Cohen 2016[152,153,154]). This has the potential to create persistent warm (where the jet stream is displaced to the north) and cold (where the jet stream moves south) weather conditions over North America.[152,153] These conditions are similar to the precursors to both the northwestern Atlantic and North Pacific heat waves.[2,134]

For biogeochemistry, other factors may amplify the global changes at the regional level as well, especially in the coastal environment. These factors include local nutrient runoff, freshwater input, glacial runoff, spatial variability in retentive mechanisms, variability in upwelling strength, cloud cover, and stability of sedimentary deposits (for example, methane).[15,125,143,151,231,233] Most of the factors will amplify the global trends toward lower oxygen and pH, leaving these estimates to be conservative. In addition, temperature, oxygen, and pH have synergistic effects that provide some uncertainties in the projected events.[56]

Description of confidence and likelihood

Because there is *very high confidence* and *very high likelihood* that oceans will get warmer, more acidified, and have lower oxygen content in response to elevated atmospheric carbon dioxide levels,[15] it is *very likely* and there is *very high confidence* that extreme events will occur with increased intensity and frequency in the future.[6,138,141,232,237]

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