Fifth National Climate Assessment: Chapter 10

Ocean Ecosystems and Marine Resources

Chapter 10. Ocean Ecosystems and Marine Resources

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Introduction

The ocean supports diverse and productive marine ecosystems that provide innumerable benefits to the United States. Fishing, recreation and tourism, energy, shipping, and transportation in the ocean and Great Lakes (see Ch. 24) sustain a marine economy that contributed over $781 billion (in 2022 dollars) to the US economy in 2021.[1] Ocean resources support human health and well-being in communities throughout the US, and sustained connections to the ocean are foundational to cultures and identities. This chapter assesses climate impacts and risks to US marine ecosystems, and to the communities and industries that depend on them, as well as ocean-based measures for climate change adaptation and mitigation.

Across the globe, climate change is altering marine ecosystems and connected social systems at a scale and pace that is unprecedented in recent millennia. The combination of long-term changes in physical ocean conditions—such as warming, sea ice loss, acidification, and deoxygenation (KMs 2.1, 3.3)—and short-term extreme events (KM 2.2) such as marine heatwaves threatens marine ecosystems and human communities (Focus on Compound Events). Numerous marine species, from phytoplankton to whales, are altering their distribution, seasonal activities, and behaviors to align with suitable ocean conditions. These changes ripple through the food web, affecting species interactions, ecosystem functions, and biodiversity, as well as conservation, management, and uses of valuable ocean resources.[2] Climate-driven changes to marine ecosystems significantly affect ocean-dependent livelihoods and, in some communities, threaten food supplies and ways of life.[3]

In affected communities, the magnitude of climate impacts and levels of adaptive capacity vary with marine resource dependence, socioeconomic status, and historical and institutionalized inequities.[4,5,6] Some individuals, communities, and industries are adapting to changes, largely through reactionary responses and, in some cases, through coordinated resilience planning.[7,8,9] However, responses are uneven across communities and sectors, and they remain insufficient to meet mounting challenges and costs.[9,10] Global policy choices regarding greenhouse gas (GHG) mitigation govern the intensity and trajectory of future climate impacts and the diversity and effectiveness of adaptation options. Mitigation and adaptation efforts require explicit accountability in social equity, sustainability goals, and fairness in governance and finance to address entrenched inequities that increase climate change risks and adaptation burdens.[5,11]

This chapter draws on global insights to address climate-related changes and challenges in US marine areas. It largely focuses on continental shelf waters, with some discussion of topics that extend shoreward to intertidal areas, and it complements Chapter 9 (Coastal Effects), which extensively covers the topic of sea level rise. The chapter builds upon the climate-related physical oceanographic changes discussed in Chapters 2 (Climate Trends) and 3 (Earth Systems Processes) to highlight some of the unprecedented ecological changes taking place in US marine waters and their impacts on social, economic, and governance systems. Policy directions, planning efforts, and investment decisions being made now will affect mitigation and adaptation options and timelines and will determine the future of our ocean and social and economic systems that rely on it.

Key Message 10.1

Unprecedented Climate Impacts Threaten Ecosystems and Human Well-Being

Climate change is significantly altering US marine ecosystems at a pace, magnitude, and extent that is unprecedented over millennia (*very high confidence*). Changes in species locations, productivity, and seasonal timing are cascading through ecosystems, threatening critical connections between people and the ocean (*high confidence*), especially for Indigenous Peoples (*very high confidence*). Risks to marine ecosystems and the people connected to them will be greater under higher scenarios (*likely*, *very high confidence*) and will depend on the ability of ecological and social systems to adapt to the pace of climate change (*very high confidence*). Continued climate change, particularly under higher scenarios, is projected to push many systems toward novel conditions and critical tipping points (*very high confidence*), beyond which the risk of significant impacts to marine ecosystems, including collapse, is high, adaptation may be insufficient, and human well-being is threatened (*high confidence*).

Observed Changes

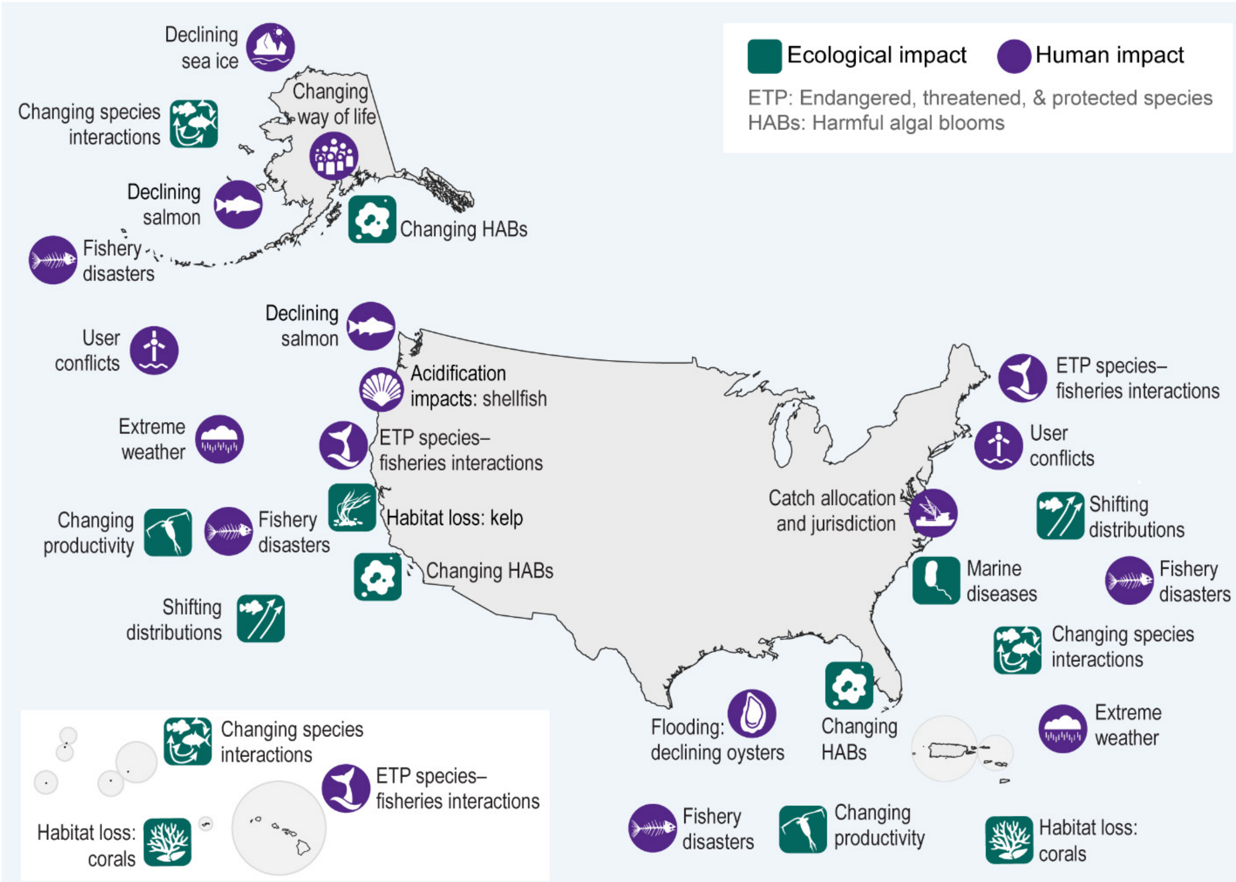
Climate-driven changes are altering marine ecosystems via complex physical, biological, and socioeconomic interactions (Figure 10.1). Many ocean characteristics, such as the timing and length of seasonal cycles, extent and duration of sea ice, oxygen content, and severity of extreme events are exhibiting major divergences from historical patterns (Box 10.1; KMs 2.2, 3.1; Figure A4.11).[10,12,13,14] Changes in distributions, population productivity, and timing of life events are widely documented for marine species and are increasing in prevalence and magnitude (Figure A4.12).[15,16,17,18,19]

Critical habitats such as coral reefs, seagrass beds, and kelp forests have experienced large-scale degradation due to climate-related stressors, threatening their ability to support commercially and ecologically important fish, shellfish, turtles, and marine mammals.[20,21,22,23] Degradation of nursery habitats, spawning areas, and other essential habitats has the potential to affect the productivity and distribution of species.[21,24]

Marine species are shifting their geographic distributions even faster than terrestrial species[25] and are changing the timing of seasonal activities.[16] As changes cascade from microbes to top predators across food webs, these shifts are decoupling some predator–prey relationships[26,27] and amplifying others.[28] For example, shifts in species have reduced prey availability for seabirds, driving large-scale starvation events and breeding-colony failures.[29,30,31]

While warming has benefitted some marine resources in poleward portions of their range (such as an increased abundance of American lobster in the Gulf of Maine[32]), many species—especially those that are cold-adapted, fixed in place, or have complex life histories—have been negatively affected.[33,34,35] Protected and endangered species with limited population resilience, including multiple species of coral, salmon, and whales, are particularly vulnerable to impacts of unfavorable physical and ecosystem conditions (KM 8.2).[22,36,37,38]

Ocean-Related Climate Impacts on People and Ecosystems



Many broad-scale climate-related ecological and human impacts are occurring in US marine areas.

Figure 10.1. Climate change is affecting marine ecosystems and impacting human activities in the US ocean. The nature of ocean-based climate impacts is often unique to local areas but can cascade through social–ecological systems to affect the entire country. For example, extreme weather events impact shipping and supply chains, and harmful algal blooms (HABs) in coastal areas affect tourism. User conflicts, such as those involving the siting of offshore renewable energy in fishing areas, have created tensions in US waters. Climate impacts on physical ocean conditions are covered in Chapters 2 and 3. Figure credit: The Nature Conservancy.

Ocean ecosystems are complex and interconnected, making it challenging to fully understand and anticipate climate-induced changes. Climate impacts are less well documented for certain ecosystem components, even ubiquitous organisms such as microbes[39] and pathogens.[40,41] Additionally, climate drivers impacting ocean ecosystems often act in complex ways and, in some cases, can originate on land. For example, altered precipitation patterns over the continental US have both reduced river flow in the Pacific Northwest and increased flooding on the Mississippi, inducing population declines in iconic species such as Chinook salmon[42] and Gulf of Mexico oysters,[43] respectively. Coastal “blue carbon” ecosystems, including coral reefs, seagrass and seaweed beds, mangrove forests, and tidal marshes, are also impacted by interactions between land- and ocean-based changes,[44,45] and these effects can extend to deep-sea ecosystems (Focus on Blue Carbon).[46,47] While US coastal and shelf ecosystems are relatively well studied, the deep ocean (below 650 feet) remains poorly studied.[48,49] The deep ocean stores and absorbs a vast quantity of carbon and heat, buffering the impacts of climate change but also resulting in warming and changes to biogeochemistry (such as deoxygenation) in this portion of the ocean (KMs 2.1, 3.4),[13,49,50] potentially impairing the health of deep-sea ecosystems and the capacity for carbon sequestration.[51]

Ocean climate impacts affect many communities, from coastal inhabitants who make a living from ocean industries to people who live far from the shore and eat fish in the US Midwest or vacation at Gulf Coast beaches. For example, harmful algal blooms (HABs) and increases in pathogens, such as *Vibrio* species, have become more prevalent in some regions, resulting in beach and fishery closures and impacting people's health and livelihoods.[52,53] Effects are amplified for Indigenous Peoples whose long-standing social, cultural, and spiritual connections to the ocean are being altered.[54,55] Subsistence harvests that are critical for food and nutritional security have been disrupted by shifts in species distributions, sea ice loss that limits access to resources, and HABs that make food sources such as razor clams, Pacific walruses, and bowhead whales unsafe for human consumption (KMs 16.1, 29.5).[56,57,58,59,60,61,62,63] Cumulatively, these changes threaten to break vital social and cultural connections by undermining food security and the mental and physical health and well-being of marine resource users.[59,64,65,66]

As impacts of climate change mount, species and people are beginning to adapt. Examples of observed adaptations include species shifting distributions as they track preferred temperatures[67] and subsistence harvesters changing what, where, and when they harvest.[68] The largest and fastest adaptation responses have followed climate impacts that occur as extreme events (e.g., heatwaves, HABs, hypoxia) or that amplify background risks and pressures (e.g., habitat degradation, resource overexploitation; Box 10.1).[69,70]

Projected Changes

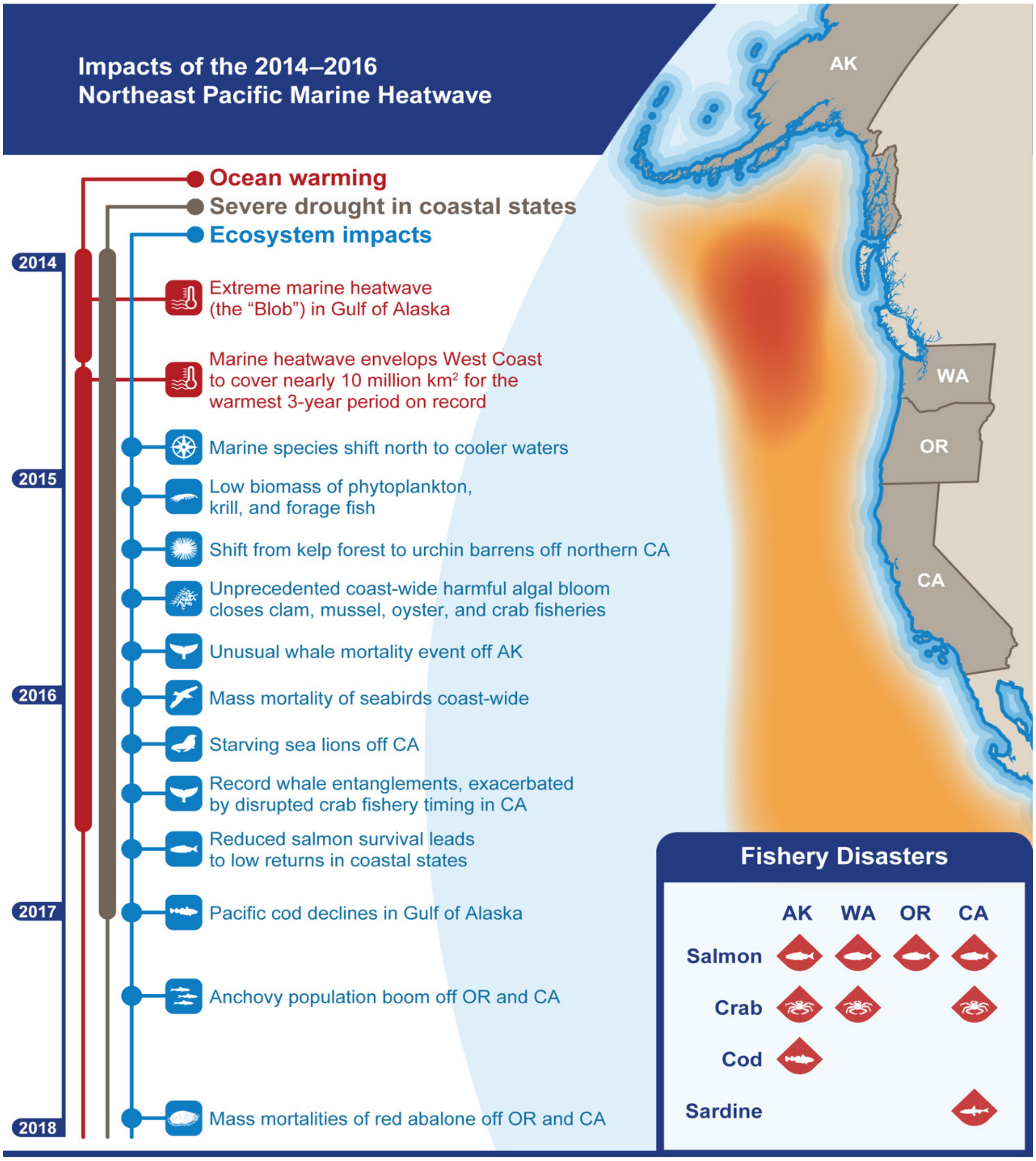
Cumulative GHG emissions will continue to affect marine ecological and social systems over the coming decades. Changes in physical and biogeochemical conditions, including temperature, stratification, upwelling, and ocean chemistry, are projected to become stronger and more widespread, particularly for higher scenarios (KM 2.3),[71] and interactions with chronic stressors such as habitat degradation or overfishing will amplify ecosystem impacts.[10] Shifts in the distribution and biomass of marine species, changes in food web structure and ecosystem functions, and increases in HABs and pathogens will be more pronounced under very high scenarios (RCP8.5, SSP5-8.5).[72,73,74,75] Climate change will drive physical and biological systems toward critical tipping points, triggering feedbacks that may threaten biodiversity, undermine system stability, permanently alter ecosystem functions and services, and limit adaptation options.[76,77,78,79]

Continued climate-driven changes pose challenges for social, economic, and governance systems, particularly those based on expectations that historical conditions will persist into the future. Shifting fish distributions are creating jurisdictional challenges for area-based management, undermining commercial fishery management approaches,[80] and jeopardizing treaty resources such as Tribes' rights to "usual and accustomed" fishing grounds.[81] The severity of impacts to marine social–ecological systems will depend on peoples' ability to adapt at the pace of climate change, which will require participatory governance systems that can effectively and equitably adjust to shifting circumstances.

Box 10.1. Cascading Impacts of a Marine Heatwave

A massive marine heatwave originated in the Gulf of Alaska in the winter of 2013/14 and subsequently encompassed the US West Coast from 2014 to 2016, producing the region's highest three-year average ocean temperature on record.[82] This event, driven by a combination of natural variability and human-caused warming,[82] had widespread impacts on ocean habitat, marine species, and human communities (Figure 10.2). These cascading impacts are illustrated by a chain of events in which, initially, cool-water habitat was compressed along the coast, causing whales to move closer to shore to feed. This shoreward shift resulted in whales foraging in Dungeness crab fishing grounds and becoming entangled in fishing gear.[83] Meanwhile, the warmer ocean and altered ocean chemistry enabled an unprecedented harmful algal bloom.[61,84] Detection of the neurotoxin domoic acid in marine species closed fisheries, delayed opening of the crab fishing season, and led to multiple fishery disaster declarations.[61] Faced with suspension of the fishing season, fishers were forced to forego revenue or shift to other fisheries;[85] adverse impacts were more pronounced for fishers with smaller vessels, who suffered disproportionately large declines in participation and revenue.[86] Finally, when the Dungeness crab fishing season opened late, increased fishing coincided with the migratory arrival of whales, producing another spike in entanglements.[83] Climate shocks like the 2014–2016 marine heatwave amplify environmental and economic impacts that can linger beyond the event itself.[70] Under future ocean warming, heatwaves will become even hotter, with historically rare temperatures occurring more frequently (KM 2.2). The increasingly novel ocean conditions in the California Current system[87] and other regions will lead to more climate surprises that create challenges for planning and decision-making.[88]

Northeast Pacific Marine Heatwave Impacts



The West Coast has experienced unprecedented warm ocean temperatures and environmental disruptions from marine heatwaves.

Figure 10.2. Heatwaves have caused extensive disruptions to marine ecosystems and, in turn, to human communities and economies. Shown here are the widespread impacts of a massive marine heatwave that began in the Gulf of Alaska and subsequently covered the entire West Coast, persisting for several years and coinciding with severe drought over land. Icons on the timeline indicate when impacts occurred; many impacts were sustained for months or years but, for clarity, are shown only at a representative time when they were particularly prevalent. Impacts described as coast-wide or without a specific location occurred off all West Coast states: Alaska, Washington, Oregon, and California. Fishery disasters, as determined by the US secretary of commerce, are shown for individual species (Pacific sardine, Pacific cod) or groups of species (salmon, crab). While the largest heatwave dissipated by 2017, effects of the 2014–2016 heatwave have persisted in the form of lasting ecological changes and new adaptation measures designed to mitigate negative impacts in the future. Figure credit: NOAA Southwest Fisheries Science Center.

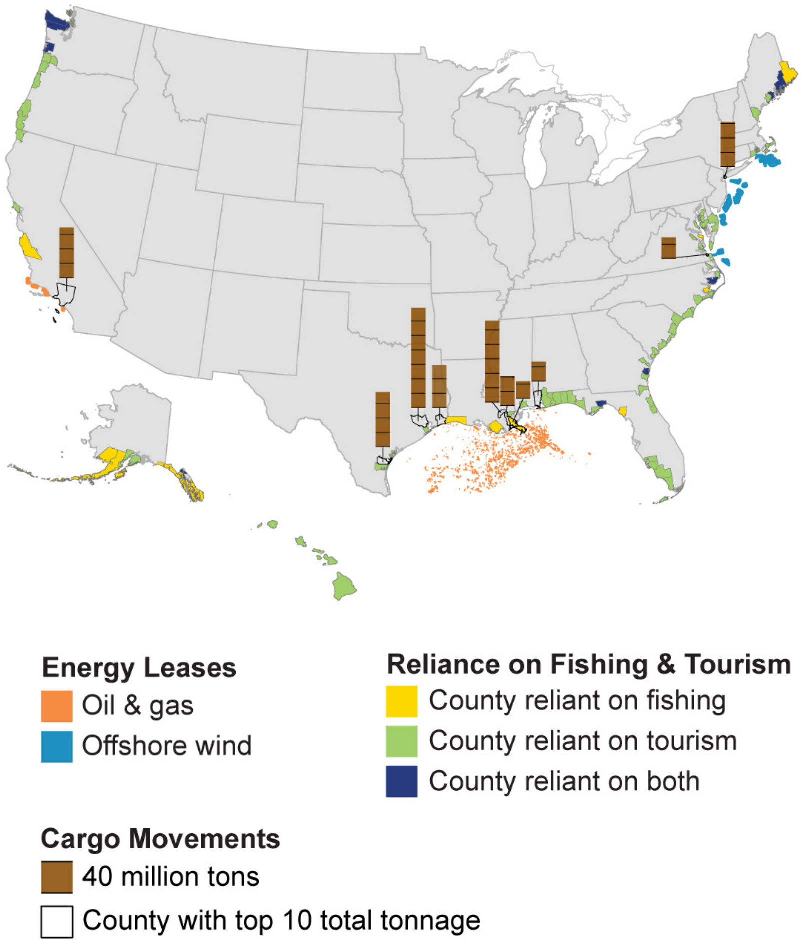
Key Message 10.2

Climate Change Is Altering Marine-Related Economic Activities

Climate change poses a substantial risk to ocean-related industries and economic activities such as fisheries, tourism, recreation, transportation, and energy (*high confidence*). As climate change continues, economic and cultural impacts are expected to become larger and more widespread, especially under higher scenarios and in communities that are highly dependent on ocean resources (*very high confidence*). A range of approaches can facilitate adaptation to some degree of climate change (*medium confidence*), but higher levels of climate change will limit the success of adaptation measures and markedly increase climate risk to marine-related economic activities (*high confidence*).

From energy to fisheries to tourism, the ocean economy is deeply intertwined with the economic health of the United States (Figure 10.3). Populations in shore-adjacent counties grew 5.3% from 2010 to 2019, with employment increasing three times as fast (16.3%). From 2005 to 2019, the ocean-related GDP grew by nearly 60% (in constant dollars), representing a total of 3.5 million jobs.[89] Ocean-based activities and industries are being affected by climate change,[90,91] and future impacts may slow growth of the ocean economy. Limiting global warming to 1.5°C (2.7°F) above preindustrial levels confers clear social and economic advantages compared to higher scenarios.[92,93]

Ocean-Based Economies



Communities throughout coastal America rely on ocean-related industries for major shares of their local economies.

Figure 10.3. Ocean industries such as fishing, shipping, and tourism are important economic activities in coastal communities across the United States. The Nation's continental shelf is a major source of energy from oil and gas, and renewable energy, particularly offshore wind, is being developed in multiple areas. The ocean-based economy is even more critical to the island commonwealths and territories in the Pacific and Caribbean, although economic data comparable to that for the 50 US states are not available. Economic dependence on ocean resources is proportionately highest in rural communities, which have fewer economic alternatives if they experience climate-related disruptions.[94,95] Figure credit: Middlebury Institute of International Studies, NOAA NCEI, and CISESS NC.

Commercial Fisheries

Climate change has impacted commercial marine fisheries in every region of the US by altering the availability and quality of harvested species, destabilizing fisheries-related revenue and employment, and inducing new management challenges.[15,69,85,96,97] The large-scale redistribution of highly valuable Bering Sea (Alaska) Pacific cod and snow crab and subsequent declines in multiple stocks, including closure of the snow crab fishery in 2022, followed low sea ice conditions and protracted warm bottom temperatures across the region (Box 10.1).[98,99,100,101,102] On the East Coast, the northern shrimp fishery collapsed and a fishing moratorium was imposed following a marine heatwave in 2012,[103] and the highest-valued single-species fishery in the US, American lobster, has seen the southern portion of its population decline to very low levels with warming waters.[32] Disaster declarations for commercial fisheries increased markedly from 1994 to 2019, with more than 84% of fishery disasters linked to extreme environmental events, totaling $3.4

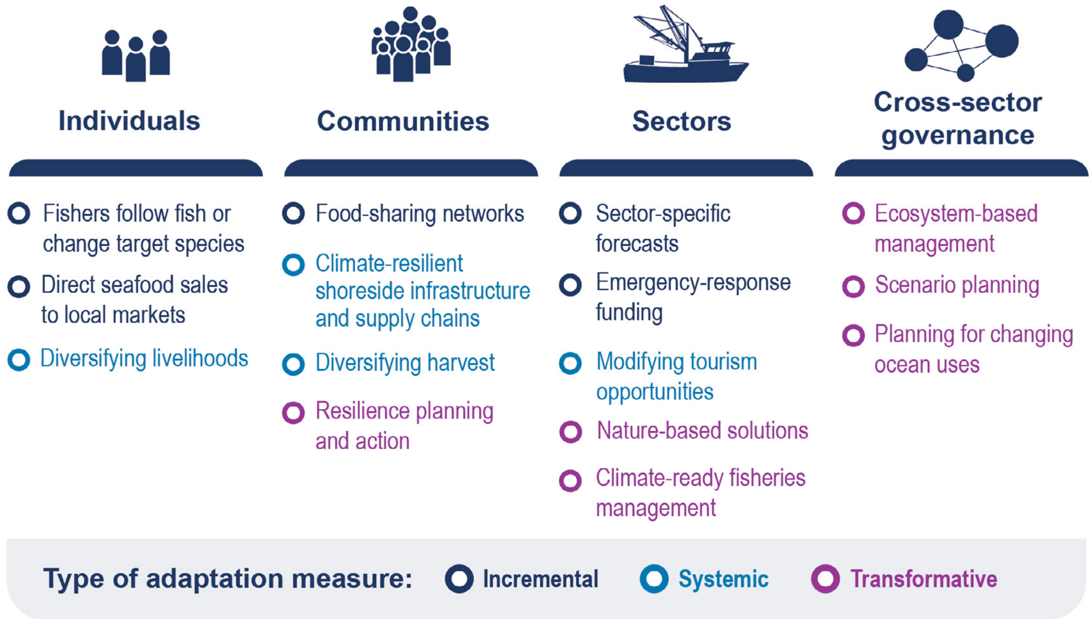
billion of lost revenue and $2.3 billion (in 2022 dollars) in federal funding for disaster relief.[104] Recent climate-related fishery declines have been widespread,[85,105,106] although a few stocks have increased with ocean warming and heatwaves (e.g., regional increases in the northern stock of American lobster, market squid, and sablefish[32,107,108]). While climate is not the sole driver impacting fish populations, it is an added stressor that exacerbates other negative impacts.[33]

Over the next century, climate change is expected to reduce catch in all US regions,[92] including some of the highest-valued fisheries (e.g., Bering Sea snow crab, walleye pollock, Pacific cod, American lobster, and Atlantic sea scallops[32,109,110,111,112]). For 16 species that represent more than half of commercial fisheries revenue, climate-induced changes are projected to result in billions of dollars of economic losses by 2100, with losses twice as high under a very high scenario (RCP8.5) than an intermediate scenario (RCP4.5).[113] Many species will continue moving northward and deeper, reducing accessibility for subsistence harvesters and smaller vessels and complicating management policies and quota allocations.[114,115,116,117,118] Severe storms and sea level rise will increasingly threaten shoreside infrastructure and transportation networks that are critical for harvesting and distributing seafood products (KM 9.1).[4,119]

Climate impacts are not distributed equally across all fisheries and can be compounded by non-climate factors, including fisheries management, market conditions, socioeconomic conditions, and external shocks (e.g., COVID-19).[4,86,115,120] Impacts are generally greater for small-scale coastal harvesters who are less able to follow shifts in fish distribution or who have access to a limited number of fish stocks, while those with larger vessels and more diverse harvest portfolios are generally more resilient.[85,86,118,121] Commercial fisheries and subsistence harvesters are adapting to these changes through short-term incremental measures, business investments appropriate for changing conditions, and management efforts supporting climate-ready fisheries (Figure 10.4).[96,122,123]

The effectiveness of future adaptation responses may be limited by the magnitude of change and factors like inequities in finance and governance across communities, costs of equipment or infrastructure, and access to fishing permits (Focus on Risks to Supply Chains).[80,97,115,124] As fisheries adapt, community initiatives such as permit banks and seafood cooperatives that plan for climate change can enhance equitable opportunities and socioeconomic benefits (Figure 10.4).[125,126] Diversifying harvest and livelihoods, including expanding into marine aquaculture (KM 11.1), can also help stabilize income or buffer risk. Tools that predict species distribution changes can help avoid bycatch, reduce costs, and increase yield.[127] Further, ecosystem-based and climate-informed management can align harvest limits with population productivity to maintain sustainable fishing levels.[109,110,128]

Ocean-Related Climate Adaptation Strategies



Adaptation can occur at many organizational scales—from individuals to governance systems.

Figure 10.4. Many types of adaptation measures are being undertaken, or are under consideration, as ways to respond to and prepare for climate change impacts on ocean activities and economic sectors. The measures range from small adjustments (incremental) to larger actions within current socioeconomic and management systems (systemic) and substantial changes beyond existing systems (transformative). Figure credit: Gulf of Maine Research Institute.

Tourism and Recreation

Ocean-based tourism and recreation—the largest sector in the ocean economy, representing $274.5 billion of economic activity in 2021 (in 2022 dollars)[1]—is both positively and negatively impacted by climate change.[129] Warming temperatures extend the coastal tourism season, yet sea level rise threatens shoreside facilities (KM 9.2) and will change nearshore wave dynamics in ways that reduce or eliminate some surfing opportunities.[130] In the Gulf of Mexico and Caribbean, worsening HABs[131] and blooms of macroalgae (e.g., *Sargassum*[132]) due to climate and local non-climate stressors have raised human health concerns (KM 23.1) that have disrupted tourism and fishing.[133,134] Recreational fisheries are experiencing climate-related changes in anglers' participation, location choices, and expenditures.[135] As warming continues, angler participation may decline by up to 15%, with losses as high as $413 million annually (in 2022 dollars) along the Atlantic and Gulf of Mexico Coasts; however, warming is increasing participation in some areas (e.g., New England).[136]

Similarly, tourism impacts are different across regions. Arctic sea ice loss is creating tourism opportunities by allowing "last-chance" cruise ship tourists to see ecosystems before they are further altered by climate change.[137] However, coral reef tourism—valued at nearly $3 billion annually for 2008–2012 (in 2022 dollars) in Hawaiʻi and Florida—is threatened by bleaching and disease that deter divers and snorkelers (KMs 23.3, 30.4).[138] At a more localized scale, the loss of endangered southern resident orca whales in Washington's Puget Sound due to climate-driven declines in food would result in annual losses of $39 million in economic activity (in 2022 dollars).[36,139]

Transportation

Climate change is already affecting marine transportation. Sea ice loss and longer open-water seasons have enabled transit between the Atlantic and Pacific via the Arctic, with ship traffic in the Arctic increasing threefold between 1990 and 2015,[140,141] and Arctic-routed shipping continues to be considered.[142] With 3.6°F (2°C) of warming above preindustrial levels, ships are projected to be able to reliably navigate the Northwest Passage and Arctic Bridge trade routes in summer.[143] These routes may reduce carbon emissions and shipping costs, but concerns exist about impacts to marine species and local communities, as well as about black carbon emissions.[54,144,145,146]

Commercial vessel emissions have increased over time, as has the sector's proportional contribution to global emissions (KM 13.1),[147] but emissions from recreational boats in the US declined between 1990 to 2021.[148] The shipping sector is initiating further measures to reduce its GHG emissions by powering docked vessels with electricity,[149] increasing vessel efficiency to reduce global shipping emissions by 50% by 2050,[147] and planning for some zero-emissions maritime routes by 2025.[150]

Energy

Ocean-based energy production in the US is in a period of transition. Ocean-based energy has been almost exclusively derived from hydrocarbon extraction, which generated $96.4 billion in 2021 (in 2022 dollars).[1] Globally, nearly 30% of commercially recoverable oil and gas assets are found in areas at high risk for climate impacts.[151] In the US, stronger hurricanes, increasing wave heights, and sea level rise will threaten offshore facilities and associated coastal structures, such as underwater pipelines and refineries (KM 9.2).[152,153] Facilities may increasingly require adaptive responses, such as raising the height of oil and gas platforms in the Gulf of Mexico to reduce hurricane damage.[154,155]

Renewable energy sources are expected to increase as part of the ocean-based energy mix over the next several decades. The first US facilities to generate electricity from ocean wind are in place off the Atlantic Coast, and in 2021, the US set a goal of installing more than 30 gigawatts of capacity by 2030, enough to power about 10 million homes.[156] States have set additional goals for offshore wind energy development that may further advance this capacity. Through 2022, more than two million acres of ocean bottom have been leased for wind energy, with more leases anticipated by 2025.[157] The growth of ocean-based renewable energy is expected to bring jobs and economic benefits to certain coastal communities, but its ecosystem impacts are still being determined, and its development may constrain other ocean uses, including fishing, transportation, and aesthetic preferences.[158,159,160,161,162]

Key Message 10.3

Our Future Ocean Depends on Decisions Today

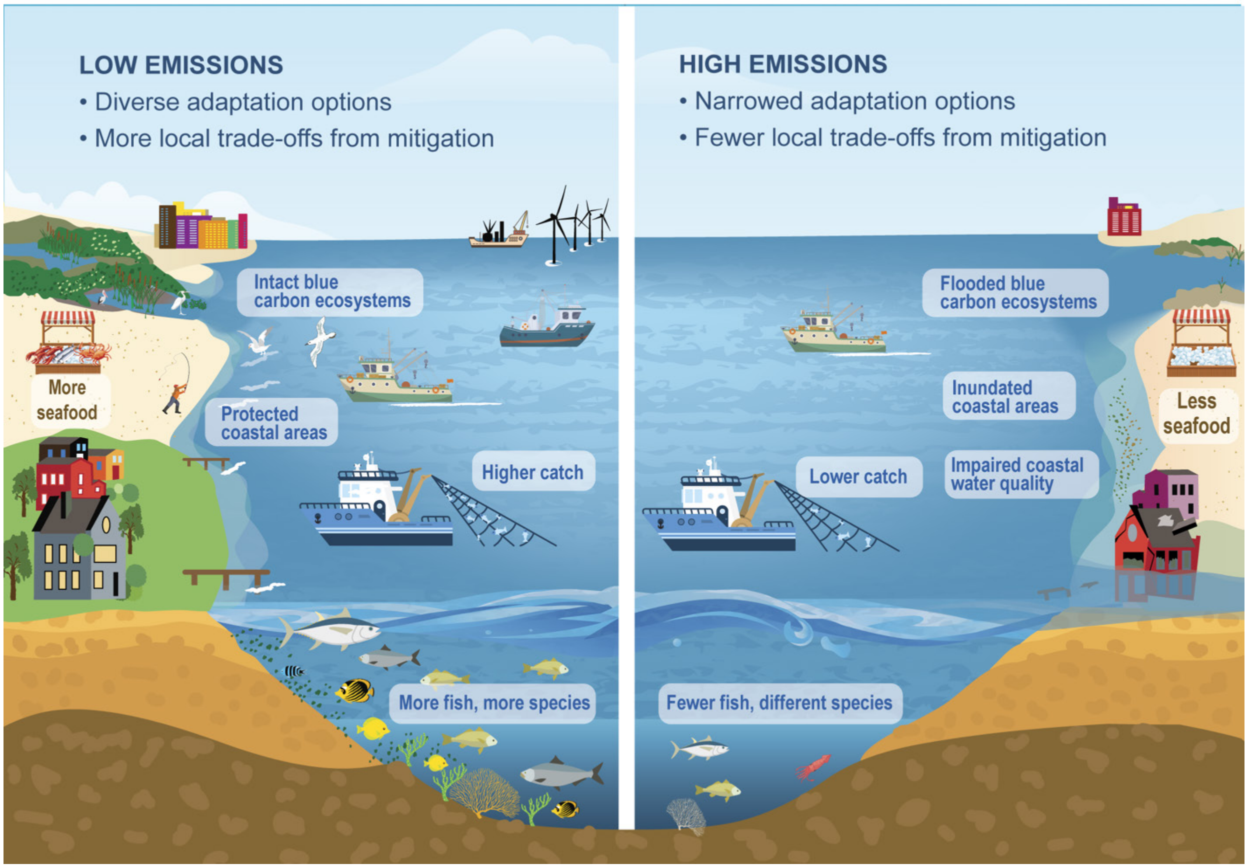
Future risks to marine ecosystems, ocean resources, and people will be substantially reduced by implementing adaptation and mitigation actions now (*very high confidence*). Responding swiftly to climate change will improve outcomes, reduce costs, promote resilience and equity, and allow the widest possible suite of adaptation solutions (*very high confidence*). Impacts will continue to be uneven across communities, with more harmful outcomes in communities that are highly ocean-reliant and historically marginalized, unless equitable adaptation and mitigation efforts are implemented (*high confidence*).

Current State of Ocean-Based Adaptation and Mitigation

Although substantial climate-driven changes in ocean ecosystems are inevitable over the coming decades (KM 2.3), the future of these systems, their valuable services, and the businesses, communities, and economies that depend on them will be determined by the choices we make now on mitigation of GHG emissions and investment in adaptation measures (Figure 10.5). Proactive, coordinated, large-scale approaches to planning, financing, and implementing adaptation measures are necessary to achieve effective and equitable outcomes (KM 31.2).[10] Reactive actions to cope with climate impacts are occurring at individual, business, and community scales but are largely uncoordinated and sometimes ineffective (Figure 10.4). Adaptive capacity is not the same across communities or groups; communities that are highly reliant on ocean resources may face the greatest risks and be constrained by socioeconomic factors, historical and ongoing inequities, and access to governance systems or financing.[4,5,163] Promising proactive adaptation-planning measures are starting to emerge in various regions and sectors. For example, some state and federal fishery-management bodies and stakeholder communities have prioritized climate preparedness and are developing information, tools, plans, and processes to address future changes and uncertainty in marine resources and fisheries.[164,165] Certain municipalities and Tribal communities are pursuing integrative climate resilience planning that considers adaptation needs across multiple ocean-related sectors (e.g., Cities of Portland and South Portland 2021;[166] Takak et al. 2021[167]).

Various ocean-based mitigation approaches are also advancing.[168] Measures to protect and restore marine ecosystems that capture and store carbon dioxide—such as mangroves, seagrasses, and kelp forests—are underway and offer additional benefits like wave energy dissipation and fisheries enhancement, but carbon mitigation benefits may be modest and variable (Focus on Blue Carbon).[10,169] Public- and private-funded projects are evaluating technical, economic, and social dimensions of ocean-based carbon dioxide removal techniques (KM 32.3; Focus on Blue Carbon).[170,171,172,173,174] Ocean-based wind energy is being implemented (KM 10.2) and wave energy conversion is being developed, especially in the Pacific basin.[175] Electric and hybrid engines for small boats[176] and expanded production of aquatic foods with lower GHG emissions[177] also support ocean-based mitigation. Estimates suggest that fully scaled-up ocean-based mitigation measures would provide about a quarter of the atmospheric GHG reduction required to meet global pledges by 2050.[172,176,178]

Ocean Conditions and Activities Under Two Climate Scenarios



Future ocean conditions and activities will depend on emissions levels and mitigation strategies.

Figure 10.5. Future marine ecosystems and human activities will differ under low versus high greenhouse gas emissions scenarios. This figure is a simplified depiction of major predicted changes as a result of climate change. Under low scenarios (**left**), more adaptation options remain available, and ocean services such as food provision and coastal protection are maintained, but trade-offs between ocean-based activities will escalate. Under high scenarios (**right**), ecosystems will be altered, fewer adaptation options will be available, and losses of services are expected across diverse sectors. Figure credit: Center for American Progress and Gulf of Maine Research Institute.

Challenges and Trade-Offs

Immediate implementation of ambitious mitigation and adaptation measures offers the greatest chance of maintaining ocean ecosystems and their benefits to people, as well as supporting equitable human development.[10] Carbon emissions peak in the mid-2020s in scenarios that limit warming to less than 3.6°F (2°C), above which risks and impacts are projected to rapidly increase across sectors and regions.[179] Without carbon mitigation, estimates indicate that a critical global warming threshold of 2.7°F (1.5°C) will be crossed in the 2030s.[179]

Coordinated adaptation planning is essential to ensure that strategies across sectors, communities, and regions are complementary and achieve equitable outcomes. Adaptation and mitigation options tend to be most successful if they are based on sound information, developed in collaboration with local communities and diverse actors, and designed to lower ecosystem and community risk.[10,180,181] Although adaptation measures are already being taken in some areas (KM 10.2), the ability to adapt is uneven across groups, communities, and sectors (KM 31.2). People with socioeconomic assets such as strong social connections, alternative livelihood options, and economic wealth are more resilient to climate disruptions,[6,85,86,182] and those with greater access to information and other resources will be better positioned to engage in adaptation efforts. Participatory planning, financial, and governance processes designed to account for divergent power dynamics and institutionalized discrimination can engage a broad array of community members in co-producing climate solutions.[181] Deliberately incorporating local knowledge, perspectives, and values can help determine efficient, enduring, and equitable adaptation and mitigation solutions.[8,180,181]

Effective climate change adaptation in marine systems also depends on implementation of carbon mitigation. Without emissions reductions, the range of possible adaptation options decreases substantially. For example, adaptation options in coral and mangrove ecosystems include reducing non-climate stressors such as pollution and prioritizing effective harvest management and habitat restoration. With increased emissions, these measures will become insufficient to maintain coral and mangroves due to warmer, more acidic conditions, and adaptations will be limited to more expensive, higher-risk options such as active translocation of species, assisted adaptation, or reef shading.[183,184] As emissions increase and the range of options for maintaining these habitats decreases, the risks of losing services they provide, such as coastal protection, livelihoods, food security, cultural identity, and tourism, are magnified.[10]

Adaptation measures with co-benefits for mitigation are especially promising. These include reef and marsh restoration, seaweed aquaculture, ecosystem-based management, and marine spatial planning. Nature-based solutions have the potential to be cost-effective and self-reinforcing over time, and if implemented at scale, they may impart climate, societal, and ecological benefits for adaptation and carbon mitigation.[185,186,187] Solutions that include equity and diversity targets and are designed through inclusive and participatory approaches have the greatest potential to both address ongoing injustices and impart benefits for marine resource users and Indigenous communities.[180,188]

Emerging technologies could further expand ocean-based mitigation, but significant uncertainties must be resolved. Research projects are exploring the design, manufacturing, and grid integration of wave, thermal, and tidal energy-capturing devices.[189] Electricity and scalable zero-emission fuels such as hydrogen are being evaluated for decarbonizing oceangoing vessels.[190] All ocean-based carbon dioxide removal techniques still require substantial research on scalability, durability of carbon storage, environmental and social impacts, governance, and financing, as well as development of suitable regulatory frameworks.[169,172,191]

Trade-offs among adaptation and mitigation activities, ecosystems, and social systems may become more challenging as more options are deployed. Ocean-based mitigation measures such as offshore wind or carbon dioxide removal could have environmental and economic impacts.[161,192] Mitigation infrastructure may affect existing activities, including fishing, boating, and shipping—which are themselves adapting to climate change.[193] Decision-making about mitigation and adaptation choices—for example, those around disproportionate environmental burdens borne by historically marginalized racial and ethnic groups or communities with fewer economic resources—also poses ethical challenges.[194] These ethical challenges may be greater for actions related to the ocean, given its complex governance systems.[195]

Needs and Opportunities

Ocean-related efforts to mitigate and adapt to climate change generally lag terrestrial efforts for several reasons, including gaps in ocean observations, lack of robust forecasts and projections, and limitations in mechanistic understandings of underlying climate-related changes. The ocean sector also faces challenges related to missing tools and services for adaptation, sector-specific (or siloed) management and governance, insufficient financing, and divergent stakeholder goals.[10] Providing equitable access to information from scientific research and local knowledge, promoting evidence-based planning and adaptive management, and implementing actions to address near- and long-term risks can help prepare for climate impacts to marine ecosystems and resources.

Data and Research

Effective and cost-sensitive responses to changing oceans entail tracking changes in social–ecological systems and using that information to address risks. Strategic expansion and coordination of ocean observations and long-term monitoring programs (inclusive of community science) are necessary to document changes across marine ecosystems.[196,197,198,199] Indigenous and local knowledge of ecosystem changes can be more fully integrated with other knowledge sources to support decision-making for ocean ecosystems.[180,200,201] Key limitations remain in tracking, understanding, and projecting changes in marine ecosystems and impacts on people and economies. In particular, limited data are available in the US Caribbean and US-Affiliated Pacific Islands. Moreover, few coordinated monitoring and information-development efforts span regional or international boundaries.[202]

Climate-relevant economic and social data are not available at temporal and geographic scales necessary for tracking how climate change impacts on the ocean affect people. Socioeconomic data, such as the number of people using the ocean for recreation, are lacking or exist only at large geographic scales that do not support analyses of local impacts or evaluation of the effectiveness of adaptation strategies.[203,204] Further, the lack of socioeconomic data precludes efforts to understand disparate impacts of and responses to climate change on communities of different sizes and income levels.

Data-Informed Management and Adaptation

Responses to climate impacts are most successful when they incorporate robust scientific information into decisions, which can be supported by research and products that are designed with end users.[205] Increased data accessibility and technical expertise focused on interpreting climate impacts and adaptation effectiveness will facilitate novel research and help deliver information that is relevant to decision-makers and stakeholders. Continued advances in near-term to decadal forecasts are urgently needed to provide decision-makers with early warnings and shape options that are incorporated into response plans, particularly for extreme events such as marine heatwaves, coral bleaching, HABs, or fish population changes.[206,207,208,209,210] Mid- and longer-term projections of changes in ocean ecosystems are necessary to support risk assessments and strategic planning.[211,212] Development of operational ocean modeling and decision support systems is a promising step to provide decision-makers with science-based information to implement adaptation measures.[122,210]

Governance and Financing

The extent of future climate impacts will depend both on the nature and magnitude of climate-related changes and on the degree to which individuals, businesses, communities, and governments can adapt to those changes.[213] The pace, scale, and scope of expected climate impacts on ocean ecosystems necessitates assessing the ability of existing governance and management frameworks to effectively respond. There is also a need for financial incentives to develop and implement mitigation and adaptation actions, including support for community and sectoral adaptation. Adaptation and mitigation choices inevitably result in trade-offs that affect possible outcomes, implementation costs, and entities that bear the costs or receive the benefits.[168] Inclusive and participatory frameworks for evaluating these trade-offs will support equitable deliberations about potential outcomes and uncertainties surrounding specific options. Such processes are especially critical for Indigenous communities with strong sociocultural connections to marine ecosystems and subsistence harvesters who rely on marine resources for food, nutritional, and economic security.[5,214] Adaptive governance systems and cross-sector, cross-scale coordinating mechanisms can help advance actions that are acceptable to multiple stakeholders.[213]

Traceable Accounts

Process Description

Author Selection

Chapter leadership considered suggestions from the Federal Register Notice process and their own networks to identify authors with topical expertise, geographic familiarity, and disciplinary perspectives that span many issues relevant to the chapter. The goal was to build a diverse team in terms of racial, ethnic, and gender diversity; career stage; involvement in past climate assessments; and representation from the academic, governmental, and nongovernmental sectors. Seventeen invitations were issued, from which a team of eight authors was assembled, including physical scientists, marine ecologists, fishery scientists, economists, and policy analysts with experience assessing climate impacts on marine ecosystems, fisheries, marine economies, and coastal communities. Authors also have expertise in conservation approaches, adaptation strategies, and management measures that may buffer climate change impacts, and several authors are engaged in research and policy analysis related to ocean-based climate mitigation options.

Literature Review and Public Engagement

Chapter authors reviewed the Fourth National Climate Assessment (NCA4) “Oceans and Marine Resources” chapter[215] and brainstormed topics for NCA5 that had emerged since then or were not well covered in NCA4. The chapter lead identified additional topics from the US Global Change Research Program (USGCRP) assessment review document and public comments. The importance of certain topics was reinforced and additional topics were identified during three public engagement workshops organized by USGCRP (January 25, 2022), the American Fisheries Society (February 1, 2022), and the Ocean Sciences Meeting (February 24, 2022). Initial topics were subsequently honed through agency review and public input. The author team routinely reevaluated the literature to incorporate scientific advances into the assessment and prioritize topics that could be covered within the space limitations.

Decision-Making Process

The chapter team held biweekly to weekly videoconferences to hone the chapter’s topics, Key Messages, and supporting information based on discussions of the state of the science. Small groups of authors developed text associated with each Key Message based on their expertise, literature review, and stakeholder input. The full author team reviewed each Key Message and its supporting information, and revisions were made until the team was satisfied with the text. The lead author administered a survey to elicit detailed input from each author on the high-level Key Message statements and the associated confidence and likelihood ratings. Differences in phrasing and ratings were discussed among the author team, and revisions were made until the group reached consensus on the content of those statements.

Key Message 10.1

Unprecedented Climate Impacts Threaten Ecosystems and Human Well-Being

Description of Evidence Base

A robust body of evidence shows that climate change is having major impacts on US marine ecosystems. Changes in physical and chemical ocean conditions (Chs. 2, 3)[10,12] affect species through distribution shifts, productivity changes, and phenology alterations.[15,16,18,19] In shallow-water habitats (coral reefs, seagrass beds, and kelp forests), climate-related declines have been documented,[20,22] but limited evidence is available to assess impacts in the deep sea.[49] In certain places (e.g., Arctic and coral reef habitats), thresholds are being reached, beyond which ecosystem functions will be eroded and systems will be permanently altered.[22,58]

Evidence documenting climate impacts on marine-dependent human communities and alterations in cultural and social interconnections, economies, and livelihoods is growing. Climate-driven ecosystem changes threaten critical social couplings that underpin the well-being, subsistence, and economic and cultural identities of many communities with strong ties to the ocean, particularly coastal and island-based Indigenous communities (KMs 29.5, 30.5).[54,163] Climate change has profoundly impacted Indigenous harvest of marine species, including those critical for subsistence.[54,56,60,62] Indigenous Knowledge continues to reveal the breadth of climate impacts on human health, ecosystems, and subsistence resources, as well as the effectiveness of adaptation measures.[57,62,63]

Evidence of future ecological and social impacts draws on climate projections to extrapolate contemporary responses into the future. Model projections show consensus on the direction of many physical and chemical changes (e.g., warming temperature, declining pH; KM 2.1).[179] Based on observed responses of species to environmental conditions and known physiological limits, populations and distributions are expected to be substantially altered by climate change.[10,72,75,78] Impacts of marine ecosystem changes on humans are expected to increase as the conditions depart further from past conditions, although the magnitude depends on the rate of change and capacity for adaptation.[213]

Major Uncertainties and Research Gaps

While overall physical and biological trends are well characterized and projected to continue, the exact scale, timing, and location of future impacts are uncertain. Uncertainty in the scale of impacts derives primarily from unclear future socioeconomic pathways (including greenhouse gas [GHG] emissions). Spread among models on the sensitivity of Earth's climate to socioeconomic futures (KM 2.1) and, in some cases, inadequate model resolution to forecast local-scale effects also contribute to uncertainty.[212] While the severity of extreme events will increase as natural variability occurs on top of a changing baseline (KM 2.2), we do not know exactly when or where extreme events will occur. Thus, the continued development of prediction systems is a priority to extend the lead time of extreme event warnings (e.g., Tommasi et al. 2017;[210] Jacox et al. 2022[206]).

Biological and ecological impacts of climate change, such as shifts in species distributions, can be assessed based on past observations. However, many existing observation systems were not deployed until recent decades,[199] with the deep ocean remaining particularly under-observed.[216] There is uncertainty associated with models of physical–biological relationships and challenges in scaling climate change impacts at the individual level to population dynamics, community interactions, or ecosystem functions. Data and studies of ecosystems and coupled social–ecological systems become scarce at large or complex scales.

Research gaps increase across the spectrum of complexity, from physical changes to system-level ecological and human impacts.[10] Baseline studies vary widely for ocean ecosystems and regions. For example, coastal ecosystems are much better observed and studied than the deep ocean, and US regions with the strongest climate signals or occurrence of extreme events (e.g., Alaska, Northeast, West Coast) have been more extensively studied than other regions. Few studies are available for assessing climate impacts to marine ecosystems, resources, and communities in non-continental US regions, such as Hawai‘i and the US-Affiliated Pacific Islands and the US Caribbean.

Description of Confidence and Likelihood

For most elements of this Key Message, the authors have decided not to assign likelihood ratings, as quantitative projections of the impacts discussed are typically focused on a specific species, process, or ecoregion. Scaling likelihoods from these focused studies up to a general message is difficult. Statements of likelihood are scenario-dependent, and studies may not use the same scenarios or compare scenarios, which limits a consistent evaluation of likelihood.

The large and growing literature on climate impacts in marine ecosystems, coupled with attribution studies demonstrating that human-caused climate change is driving ocean conditions beyond the envelope of historical variability, give *very high confidence* that we have entered an unprecedented period of climate-driven marine ecosystem change.[179,213] Studies of biological responses to climate change are widespread, but there is somewhat less research documenting how the cascading impacts of physical and ecological ocean changes affect human communities. The available information indicates that impacts are predominantly neutral or negative, leading to *high confidence* in our understanding of impacts to livelihoods, cultures, food supplies, and other human-ocean connections.[10] A number of studies have focused on impacts to Indigenous Peoples, indicating *very high confidence* that climate change is altering ways of life, cultural traditions, and connections to the ocean for many Indigenous groups.[54,58,68] The scientific literature overwhelmingly projects that climate-driven changes in social–ecological systems will become more frequent and intense as human-caused climate change emerges further from natural climate variability, with the greatest impacts under high or very high scenarios.[72,75] Because a large evidence base consistently projects higher risks to marine ecosystems under higher scenarios, this outcome is considered *likely*, with *very high confidence*. While there is uncertainty about the pace and effectiveness of adaptation in social–ecological systems, there is *very high confidence* that the risks will be elevated if the pace of adaptation does not match or exceed the pace of climate change. The existence of ecological tipping points is supported by theory and empirical evidence (e.g., Hoegh-Guldberg et al. 2019;[77] Stewart-Sinclair et al. 2020;[79] Penn and Deutsch 2022[78]), and the authors have *very high confidence* that many systems are moving toward tipping points and that some will be crossed in the future. This confidence is highest in ecosystems such as coral reefs that are experiencing frequent bleaching events and die-offs[10] and in the Arctic, where declining sea ice is altering the ecosystem and social–ecological connections (KM 29.5). The authors have *high confidence* that as ecosystems move toward tipping points, interconnected social systems will be fundamentally changed in ways that threaten the well-being of people and communities.[76]

Key Message 10.2

Climate Change Is Altering Marine-Related Economic Activities

Description of Evidence Base

Studies characterize the observed and projected impact of climate change on US commercial marine fisheries. These include temperature impacts on productivity and redistribution of species and dependent fisheries, communities, supply chains, markets, and fisheries management.[15,69,85,96,97,100,118,121] Commercial fisheries and subsistence harvesters are adapting to these changes through shifts in fishing locations, target species, harvest diversification, and other strategies, yet adaptive capacity varies across different types of harvesters and communities.[68,85,118,163] Projections of how climate change will affect fisheries are available for many of the largest US commercial fisheries (e.g., Rheuban et al. 2017;[111] Le Bris et al. 2018;[32] Holsman et al. 2020;[110] Moore et al. 2021[113]). However, the magnitude of impacts differs across models that vary in resolution, complexity, and inclusion of regional management measures.[109,217]

Several studies characterize temperature- and weather-driven changes to human behavior around tourism and recreation,[130,135,136] as well as direct impacts to resources that drive tourism.[36,138,139] The data needed to quantify impacts and benefits of mitigation efforts in the transportation sector are more limited, although there has been a strong focus on the Arctic.[54,60,140,143] Sea level rise will also threaten ocean transportation and shoreside infrastructure (KM 9.2).

Studies have determined that climate change, particularly sea level rise and stronger storms, poses a direct threat to ocean-based oil and gas infrastructure,[155] as well as an indirect increase in the risk of oil spills due to climate change.[154] For offshore wind, studies have estimated production capacity and variability off the US coasts and described potential impacts to surrounding ecosystems[161,192] and existing ocean uses.[158,160,162]

Major Uncertainties and Research Gaps

Scientific literature associated with climate impacts and adaptive responses in ocean-based industries is developed and growing for commercial fisheries but is limited for many other sectors. Although tourism represents the largest sector of the ocean economy, there are relatively few studies that project climate impacts to the US ocean tourism sector at regional to national scales. Those that are available focus on specific industries in specific locations, such as cruising in the Arctic,[137] coral reef tourism in Florida and Hawai‘i,[138] and whale watching in Puget Sound.[139] Studies of climate impacts on marine recreational fisheries are also limited,[135,136] particularly compared to extensive studies of commercial fisheries. Efforts to reduce GHG emissions from vessels, ports, and shipping are developing,[147,149] but limited data availability makes it difficult to track associated implementation progress and emission outcomes. Syntheses of the state of knowledge related to ecological, economic, and community impacts of the development of ocean-based renewable energy are just recently becoming available.[159]

The greatest limitation in understanding economic and social impacts of climate change on marine-dependent livelihoods stems from the lack of publicly available economic and social data—specifically at spatial and temporal scales necessary to track changes, measure impacts, and make projections for marine economic sectors.[218] This gap constrains efforts to quantify the magnitude of impacts, effectiveness of adaptation strategies, and differential impacts and responses across distinct groups. A nascent area of study concerns the interacting and compounding ecological, social, economic, and cultural impacts of changes on the social–ecological systems with which marine industries interact.

Description of Confidence and Likelihood

Across numerous studies, there is high agreement and robust evidence, and therefore *high confidence*, that climate change poses significant risk to marine economic sectors and activities. This evidence includes various determinations of climate change risk from recent assessment reports with focused chapters on marine sectors and communities (e.g., Constable et al. 2022;[219] Cooley et al. 2022;[10] Hicke et al. 2022[7]). Multiple studies have evaluated risk over time under contrasting future carbon mitigation scenarios; high agreement in results yields *very high confidence* that climate change impacts increase over time and with higher levels of global warming, posing higher risks to communities and groups that have fewer economic alternatives and lower adaptive capacity.[179,213] The impacts of ocean-based climate change depend on the effectiveness and feasibility of adaptation measures that remain largely nascent,[10] leading to *medium confidence* that adaptation measures can help reduce the impacts of climate change. Adaptation options narrow and challenges of adaptation increase with greater magnitude and complexity of impacts,[7,10] giving *high confidence* in the limits of adaptation under higher scenarios. Quantitative projections of climate impacts on marine economy sectors are few and location-specific, and they do not use multiple or comparable climate scenarios; as such, the authors have decided not to apply likelihood ratings.

Key Message 10.3

Our Future Ocean Depends on Decisions Today

Description of Evidence Base

There is abundant evidence that the severity and rate of future climate impacts on ocean systems and ocean-reliant human communities will vary based on GHG trajectories, which are the outcomes of societal choices (KMs 2.3, 3.1). Local, regional, and sectoral impacts will be influenced by the pace and effectiveness of adaptation efforts.[10]

An increasing number of efforts indicate the potential for ocean-based mitigation and adaptation solutions. Advances in mitigation are being realized through the production of ocean-based renewable energy,[156,157] decarbonization of the maritime shipping industry (KM 13.2),[147] and expansion of aquatic food systems with lower overall emissions (KM 11.1).[177] In addition, nature-based solutions such as the preservation and restoration of blue carbon ecosystems (Focus on Blue Carbon)[220] and carbon dioxide removal techniques that leverage ocean systems and enhance the ocean's natural carbon sink (KM 32.3)[172] may offer cost-efficient and effective approaches that support carbon mitigation, climate adaptation, and biodiversity.[185,186,221] However, the benefits for adaptation and biodiversity are presently more clear than long-term benefits for mitigation (e.g., carbon sequestration), and more research would be needed to understand scales at which mitigation benefits are realized, rates of benefit growth over time, and the effectiveness of specific measures relative to other mitigation options.[187,222]

Even with swift and ambitious reductions in GHG emissions, climate impacts to oceans will continue.[179] Existing studies document how ocean users, economic sectors, and communities in the US are reacting to climate impacts with a variety of strategies, including business changes, early warning systems, evidence-based management, resilience planning, governance adjustments, and technological innovations.[10,69,96,122] Disparities are expected because not all individuals and communities are equally able to adapt, yet few studies exist to understand the types of disparities that are arising, how they are distributed among different communities and groups, and the extent to which they are mediated by factors such as social connectivity, wealth, or the diversity of available livelihood options.[4,86,182]

There is increasing evidence that adaptation strategies that are highly coordinated, planned in advance, and applied to larger scales lead to more durable, equitable outcomes.[7,10] Regardless of the adaptation approach, there is strong and abundant evidence that with continued increases in emissions, the number of effective adaptation options will decrease.[213] Plentiful and diverse evidence from the US and worldwide indicates that future conditions will make it more difficult to maintain ecological, social, cultural, and economic interconnections related to ocean ecosystems.[213]

Major Uncertainties and Research Gaps

A greater understanding of the relative benefits and risks of adaptation strategies, conditions that influence effectiveness, feasibility of uptake by different groups of people, and implementation costs is needed. Limited data and research are available to quantify the socioeconomic impacts of climate change and how they vary among communities or groups or to evaluate how social conditions and interactions (e.g., economic, governance, or social coordination) influence choices, implementation, and effectiveness of adaptation options.[10] Limits to adaptation are not yet well known for ecosystems, individuals, and communities. Whether certain conditions, such as social connectivity, flexibility, socioeconomic assets, and livelihood diversity,[4,182] insulate marine resource users from climate impacts and how they can be enhanced are still emerging areas of understanding.

How ocean-based mitigation solutions would affect marine ecosystems, existing uses of the ocean, and marine-dependent human communities is not yet well understood. The GHG-reduction potential and costs of many ocean-based mitigation options are still highly uncertain, and more information is needed to fully assess their effectiveness, scalability, and affordability.[169,176] There is an emerging body of information about how offshore wind development may affect the surrounding physical and natural system,[159] and some of these insights may apply to techniques under development, such as ocean carbon dioxide removal. Development of new ocean uses is expected to alter access for other activities, but it is unclear how adaptation strategies and mitigation measures may influence ocean use patterns and the types of users who may be advantaged or disadvantaged by these changes.[193]

The strong relationship between ambitious mitigation and a larger portfolio of effective adaptations is recognized across many ecosystems and sectors. However, data exist for only a limited number of ocean ecosystems, such as warm-water coral reefs and mangroves,[10] and additional ocean-focused studies would improve understanding. There is relatively little information on trade-offs among adaptation choices or interactions between ocean-focused adaptation, mitigation, and prevailing social conditions. These connections are mainly derived from analogy with coastal and terrestrial systems, where evidence about human–natural system decision-making tends to be more available.

Description of Confidence and Likelihood

Across a range of studies, climate change impacts are affecting marine social–ecological systems, and risks are projected to increase in the future.[213] Projections consistently indicate that risks to marine social–ecological systems are lower under climate scenarios that achieve high mitigation and adaptation and that are implemented sooner, yielding *very high confidence* in this pattern of outcomes.[10] A broader array of adaptation options will be preserved if they are implemented sooner and keep pace with the rate of climate change impacts,[7,10] giving *very high confidence* that earlier adaptation will enhance outcomes and reduce costs. Impacts are being observed in communities that heavily depend on marine resources and have limited capacity to adapt, including Indigenous communities, resource-dependent economies, and smaller-scale fisheries.[58,68,86,118,163] These studies give *high confidence* that impacts are uneven and that intentional considerations that promote equitable mitigation and adaptation are required to reduce disproportionate impacts.

References

1. BEA, 2023: Marine Economy Satellite Account, 2021: New Statistics for 2021; 2014–2020 Updated. BEA 23-24. U.S. Department of Commerce, Bureau of Economic Analysis. https://www.bea.gov/sites/default/files/2023-06/mesa0623.pdf

2. Pecl, G.T., M.B. Araújo, J.D. Bell, J. Blanchard, T.C. Bonebrake, I.-C. Chen, T.D. Clark, R.K. Colwell, F. Danielsen, B. Evengård, L. Falconi, S. Ferrier, S. Frusher, R.A. Garcia, R.B. Griffis, A.J. Hobday, C. Janion-Scheepers, M.A. Jarzyna, S. Jennings, J. Lenoir, H.I. Linnetved, V.Y. Martin, P.C. McCormack, J. McDonald, N.J. Mitchell, T. Mustonen, J.M. Pandolfi, N. Pettorelli, E. Popova, S.A. Robinson, B.R. Scheffers, J.D. Shaw, C.J.B. Sorte, J.M. Strugnell, J.M. Sunday, M.-N. Tuanmu, A. Vergés, C. Villanueva, T. Wernberg, E. Wapstra, and S.E. Williams, 2017: Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science*, **355** (6332), eaai9214. https://doi.org/10.1126/science.aai9214

3. Tigchelaar, M., W.W.L. Cheung, E.Y. Mohammed, M.J. Phillips, H.J. Payne, E.R. Selig, C.C.C. Wabnitz, M.A. Oyinlola, T.L. Frölicher, J.A. Gephart, C.D. Golden, E.H. Allison, A. Bennett, L. Cao, J. Fanzo, B.S. Halpern, V.W.Y. Lam, F. Micheli, R.L. Naylor, U.R. Sumaila, A. Tagliabue, and M. Troell, 2021: Compound climate risks threaten aquatic food system benefits. *Nature Food*, **2** (9), 673–682. https://doi.org/10.1038/s43016-021-00368-9

4. Colburn, L.L., M. Jepson, C. Weng, T. Seara, J. Weiss, and J.A. Hare, 2016: Indicators of climate change and social vulnerability in fishing dependent communities along the Eastern and Gulf Coasts of the United States. *Marine Policy*, **74**, 323–333. https://doi.org/10.1016/j.marpol.2016.04.030

5. Crosman, K.M., E.H. Allison, Y. Ota, A.M. Cisneros-Montemayor, G.G. Singh, W. Swartz, M. Bailey, K.M. Barclay, G. Blume, M. Colléter, M. Fabinyi, E.M. Faustman, R. Fielding, P.J. Griffin, Q. Hanich, H. Harden-Davies, R.P. Kelly, T.-A. Kenny, T. Klinger, J.N. Kittinger, K. Nakamura, A.P. Pauwelussen, S. Pictou, C. Rothschild, K.L. Seto, and A.K. Spalding, 2022: Social equity is key to sustainable ocean governance. *npj Ocean Sustainability*, **1** (1), 4. https://doi.org/10.1038/s44183-022-00001-7

6. Mason, J.G., J.G. Eurich, J.D. Lau, W. Battista, C.M. Free, K.E. Mills, K. Tokunaga, L.Z. Zhao, M. Dickey-Collas, M. Valle, G.T. Pecl, J.E. Cinner, T.R. McClanahan, E.H. Allison, W.R. Friedman, C. Silva, E. Yáñez, M.Á. Barbieri, and K.M. Kleisner, 2022: Attributes of climate resilience in fisheries: From theory to practice. *Fish and Fisheries*, **23** (3), 522–544. https://doi.org/10.1111/faf.12630

7. Hicke, J.A., S. Lucatello, L.D. Mortsch, J. Dawson, M.D. Aguilar, C.A.F. Enquist, E.A. Gilmore, D.S. Gutzler, S. Harper, K. Holsman, E.B. Jewett, T.A. Kohler, and K. Miller, 2022: Ch. 14. North America. In: *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1929–2042. https://doi.org/10.1017/9781009325844.016

8. Schipper, E.L.F., A. Revi, B.L. Preston, E.R. Carr, S.H. Eriksen, L.R. Fernandez-Carril, B.C. Glavovic, N.J.M. Hilmi, D. Ley, R. Mukerji, M.S.M.d. Araujo, R. Perez, S.K. Rose, and P.K. Singh, 2022: Ch. 18. Climate resilient development pathways. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2655–2807. https://doi.org/10.1017/9781009325844.027

9. Trebilco, R., A. Fleming, A.J. Hobday, J. Melbourne-Thomas, A. Meyer, J. McDonald, P.C. McCormack, K. Anderson, N. Bax, S.P. Corney, L.X.C. Dutra, H.E. Fogarty, J. McGee, K. Mustonen, T. Mustonen, K.A. Norris, E. Ogier, A.J. Constable, and G.T. Pecl, 2022: Warming world, changing ocean: Mitigation and adaptation to support resilient marine systems. *Reviews in Fish Biology and Fisheries*, **32** (1), 39–63. https://doi.org/10.1007/s11160-021-09678-4

10. Cooley, S., D. Schoeman, L. Bopp, P. Boyd, S. Donner, D.Y. Ghebrehiwet, S.-I. Ito, W. Kiessling, P. Martinetto, E. Ojea, M.-F. Racault, B. Rost, and M. Skern-Mauritzen, 2022: Ch. 3. Oceans and coastal ecosystems and their services. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 379–550. https://doi.org/10.1017/9781009325844.005

11. Bennett, N.J., A.M. Cisneros-Montemayor, J. Blythe, J.J. Silver, G. Singh, N. Andrews, A. Calò, P. Christie, A. Di Franco, E.M. Finkbeiner, S. Gelcich, P. Guidetti, S. Harper, N. Hotte, J.N. Kittinger, P. Le Billon, J. Lister, R. López de la Lama, E. McKinley, J. Scholtens, A.-M. Solås, M. Sowman, N. Talloni-Álvarez, L.C.L. Teh, M. Voyer, and U.R. Sumaila, 2019: Towards a sustainable and equitable blue economy. *Nature Sustainability*, **2** (11), 991–993. https://doi.org/10.1038/s41893-019-0404-1

12. Gruber, N., P.W. Boyd, T.L. Frölicher, and M. Vogt, 2021: Biogeochemical extremes and compound events in the ocean. *Nature*, **600** (7889), 395–407. https://doi.org/10.1038/s41586-021-03981-7

13. IPCC, 2019: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Pörtner, H.-O., D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, and N.M. Weyer, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 755 pp. https://doi.org/10.1017/9781009157964

14. Trainer, V.L., S.K. Moore, G. Hallegraeff, R.M. Kudela, A. Clement, J.I. Mardones, and W.P. Cochlan, 2020: Pelagic harmful algal blooms and climate change: Lessons from nature's experiments with extremes. *Harmful Algae*, **91**, 101591. https://doi.org/10.1016/j.hal.2019.03.009

15. Free, C.M., J.T. Thorson, M.L. Pinsky, K.L. Oken, J. Wiedenmann, and O.P. Jensen, 2019: Impacts of historical warming on marine fisheries production. *Science*, **363** (6430), 979–983. https://doi.org/10.1126/science.aau1758

16. Langan, J.A., G. Puggioni, C.A. Oviatt, M.E. Henderson, and J.S. Collie, 2021: Climate alters the migration phenology of coastal marine species. *Marine Ecology Progress Series*, **660**, 1–18. https://doi.org/10.3354/meps13612

17. Pinsky, M.L., B. Worm, M.J. Fogarty, J.L. Sarmiento, and S.A. Levin, 2013: Marine taxa track local climate velocities. *Science*, **341** (6151), 1239–1242. https://doi.org/10.1126/science.1239352

18. Staudinger, M.D., K.E. Mills, K. Stamieszkin, N.R. Record, C.A. Hudak, A. Allyn, A. Diamond, K.D. Friedland, W. Golet, M.E. Henderson, C.M. Hernandez, T.G. Huntington, R. Ji, C.L. Johnson, D.S. Johnson, A. Jordaan, J. Kocik, Y. Li, M. Liebman, O.C. Nichols, D. Pendleton, R.A. Richards, T. Robben, A.C. Thomas, H.J. Walsh, and K. Yakola, 2019: It's about time: A synthesis of changing phenology in the Gulf of Maine ecosystem. *Fisheries Oceanography*, **28** (5), 532–566. https://doi.org/10.1111/fog.12429

19. Tableau, A., J.S. Collie, R.J. Bell, and C. Minto, 2019: Decadal changes in the productivity of New England fish populations. *Canadian Journal of Fisheries and Aquatic Sciences*, **76** (9), 1528–1540. https://doi.org/10.1139/cjfas-2018-0255

20. Beas-Luna, R., F. Micheli, C.B. Woodson, M. Carr, D. Malone, J. Torre, C. Boch, J.E. Caselle, M. Edwards, J. Freiwald, S.L. Hamilton, A. Hernandez, B. Konar, K.J. Kroeker, J. Lorda, G. Montaño-Moctezuma, and G. Torres-Moye, 2020: Geographic variation in responses of kelp forest communities of the California Current to recent climatic changes. *Global Change Biology*, **26** (11), 6457–6473. https://doi.org/10.1111/gcb.15273

21. Farr, E.R., M.R. Johnson, M.W. Nelson, J.A. Hare, W.E. Morrison, M.D. Lettrich, B. Vogt, C. Meaney, U.A. Howson, P.J. Auster, F.A. Borsuk, D.C. Brady, M.J. Cashman, P. Colarusso, J.H. Grabowski, J.P. Hawkes, R. Mercaldo-Allen, D.B. Packer, and D.K. Stevenson, 2021: An assessment of marine, estuarine, and riverine habitat vulnerability to climate change in the Northeast U.S. *PLoS ONE*, **16** (12), e0260654. https://doi.org/10.1371/journal.pone.0260654

22. Hughes, T.P., M.L. Barnes, D.R. Bellwood, J.E. Cinner, G.S. Cumming, J.B.C. Jackson, J. Kleypas, I.A. van de Leemput, J.M. Lough, T.H. Morrison, S.R. Palumbi, E.H. van Nes, and M. Scheffer, 2017: Coral reefs in the Anthropocene. *Nature*, **546**, 82–90. https://doi.org/10.1038/nature22901

23. Smale, D.A., 2020: Impacts of ocean warming on kelp forest ecosystems. *New Phytologist*, **225** (4), 1447–1454. https://doi.org/10.1111/nph.16107

24. Tonina, D., J.A. McKean, D. Isaak, R.M. Benjankar, C. Tang, and Q. Chen, 2022: Climate change shrinks and fragments salmon habitats in a snow-dependent region. *Geophysical Research Letters*, **49** (12), e2022GL098552. https://doi.org/10.1029/2022gl098552

25. Lenoir, J., R. Bertrand, L. Comte, L. Bourgeaud, T. Hattab, J. Murienne, and G. Grenouillet, 2020: Species better track climate warming in the oceans than on land. *Nature Ecology & Evolution*, **4** (8), 1044–1059. https://doi.org/10.1038/s41559-020-1198-2

26. Laurel, B.J., M.E. Hunsicker, L. Ciannelli, T.P. Hurst, J. Duffy-Anderson, R. O'Malley, and M. Behrenfeld, 2021: Regional warming exacerbates match/mismatch vulnerability for cod larvae in Alaska. *Progress in Oceanography*, **193**, 102555. https://doi.org/10.1016/j.pocean.2021.102555

27. Thorne, L.H. and J.A. Nye, 2021: Trait-mediated shifts and climate velocity decouple an endothermic marine predator and its ectothermic prey. *Scientific Reports*, **11** (1), 18507. https://doi.org/10.1038/s41598-021-97318-z

28. McMahan, M.D., G.D. Sherwood, and J.H. Grabowski, 2020: Geographic variation in life-history traits of black sea bass (*Centropristis striata*) during a rapid range expansion. *Frontiers in Marine Science*, **7**, 567758. https://doi.org/10.3389/fmars.2020.567758

29. Kress, S.W., P. Shannon, C. O'Neal, and S. Cooke, 2017: Recent changes in the diet and survival of Atlantic puffin chicks in the face of climate change and commercial fishing in midcoast Maine, USA. *FACETS*, **1**, 27–43. https://doi.org/10.1139/facets-2015-0009

30. Piatt, J.F., J.K. Parrish, H.M. Renner, S.K. Schoen, T.T. Jones, M.L. Arimitsu, K.J. Kuletz, B. Bodenstein, M. García-Reyes, R.S. Duerr, R.M. Corcoran, R.S.A. Kaler, G.J. McChesney, R.T. Golightly, H.A. Coletti, R.M. Suryan, H.K. Burgess, J. Lindsey, K. Lindquist, P.M. Warzybok, J. Jahncke, J. Roletto, and W.J. Sydeman, 2020: Extreme mortality and reproductive failure of common murres resulting from the northeast Pacific marine heatwave of 2014–2016. *PLoS ONE*, **15** (1), e0226087. https://doi.org/10.1371/journal.pone.0226087

31. Scopel, L., A. Diamond, S. Kress, and P. Shannon, 2019: Varied breeding responses of seabirds to a regime shift in prey base in the Gulf of Maine. *Marine Ecology Progress Series*, **626**, 177–196. https://doi.org/10.3354/meps13048

32. Le Bris, A., K.E. Mills, R.A. Wahle, Y. Chen, M.A. Alexander, A.J. Allyn, J.G. Schuetz, J.D. Scott, and A.J. Pershing, 2018: Climate vulnerability and resilience in the most valuable North American fishery. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (8), 1831–1836. https://doi.org/10.1073/pnas.1711122115

33. Hare, J.A., W.E. Morrison, M.W. Nelson, M.M. Stachura, E.J. Teeters, R.B. Griffis, M.A. Alexander, J.D. Scott, L. Alade, R.J. Bell, A.S. Chute, K.L. Curti, T.H. Curtis, D. Kircheis, J.F. Kocik, S.M. Lucey, C.T. McCandless, L.M. Milke, D.E. Richardson, E. Robillard, H.J. Walsh, M.C. McManus, K.E. Marancik, and C.A. Griswold, 2016: A vulnerability assessment of fish and invertebrates to climate change on the northeast U.S. continental shelf. *PLoS ONE*, **11** (2), e0146756. https://doi.org/10.1371/journal.pone.0146756

34. McClure, M.M., M.A. Haltuch, E. Willis-Norton, D.D. Huff, E.L. Hazen, L.G. Crozier, M.G. Jacox, M.W. Nelson, K.S. Andrews, L.A.K. Barnett, A.M. Berger, S. Beyer, J. Bizzarro, D. Boughton, J.M. Cope, M. Carr, H. Dewar, E. Dick, E. Dorval, J. Dunham, V. Gertseva, C.M. Greene, R.G. Gustafson, O.S. Hamel, C.J. Harvey, M.J. Henderson, C.E. Jordan, I.C. Kaplan, S.T. Lindley, N.J. Mantua, S.E. Matson, M.H. Monk, P. Moyle, C. Nicol, J. Pohl, R.R. Rykaczewski, J.F. Samhouri, S. Sogard, N. Tolimieri, J. Wallace, C. Wetzel, and S.J. Bograd, 2023: Vulnerability to climate change of managed stocks in the California Current Large Marine Ecosystem. *Frontiers in Marine Science*, **10**, 1103767. https://doi.org/10.3389/fmars.2023.1103767

35. Raymond, W.W., J.S. Barber, M.N. Dethier, H.A. Hayford, C.D.G. Harley, T.L. King, B. Paul, C.A. Speck, E.D. Tobin, A.E.T. Raymond, and P.S. McDonald, 2022: Assessment of the impacts of an unprecedented heatwave on intertidal shellfish of the Salish Sea. *Ecology*, **103** (10), e3798. https://doi.org/10.1002/ecy.3798

36. Crozier, L.G., M.M. McClure, T. Beechie, S.J. Bograd, D.A. Boughton, M. Carr, T.D. Cooney, J.B. Dunham, C.M. Greene, M.A. Haltuch, E.L. Hazen, D.M. Holzer, D.D. Huff, R.C. Johnson, C.E. Jordan, I.C. Kaplan, S.T. Lindley, N.J. Mantua, P.B. Moyle, J.M. Myers, M.W. Nelson, B.C. Spence, L.A. Weitkamp, T.H. Williams, and E. Willis-Norton, 2019: Climate vulnerability assessment for Pacific salmon and steelhead in the California Current Large Marine Ecosystem. *PLoS ONE*, **14** (7), e0217711. https://doi.org/10.1371/journal.pone.0217711

37. Meyer-Gutbrod, E.L., C.H. Greene, K.T.A. Davies, and D.G. Johns, 2021: Ocean regime shift is driving collapse of the North Atlantic right whale population. *Oceanography*, **34** (3), 22–31. https://doi.org/10.5670/oceanog.2021.308

38. Mills, K.E., A.J. Pershing, T.F. Sheehan, and D. Mountain, 2013: Climate and ecosystem linkages explain widespread declines in North American Atlantic salmon populations. *Global Change Biology*, **19** (10), 3046–3061. https://doi.org/10.1111/gcb.12298

39. Trombetta, T., F. Vidussi, C. Roques, M. Scotti, and B. Mostajir, 2020: Marine microbial food web networks during phytoplankton bloom and non-bloom periods: Warming favors smaller organism interactions and intensifies trophic cascade. *Frontiers in Microbiology*, **11**, 502336. https://doi.org/10.3389/fmicb.2020.502336

40. Carlson, C.J., S. Hopkins, K.C. Bell, J. Doña, S.S. Godfrey, M.L. Kwak, K.D. Lafferty, M.L. Moir, K.A. Speer, G. Strona, M. Torchin, and C.L. Wood, 2020: A global parasite conservation plan. *Biological Conservation*, **250**, 108596. https://doi.org/10.1016/j.biocon.2020.108596

41. Wood, C.L., R.L. Welicky, W.C. Preisser, K.L. Leslie, N. Mastick, C. Greene, K.P. Maslenikov, L. Tornabene, J.M. Kinsella, and T.E. Essington, 2023: A reconstruction of parasite burden reveals one century of climate-associated parasite decline. *Proceedings of the National Academy of Sciences of the United States of America*, **120** (3), e2211903120. https://doi.org/10.1073/pnas.2211903120

42. Ward, E.J., J.H. Anderson, T.J. Beechie, G.R. Pess, and M.J. Ford, 2015: Increasing hydrologic variability threatens depleted anadromous fish populations. *Global Change Biology*, **21** (7), 2500–2509. https://doi.org/10.1111/gcb.12847

43. Wang, H., Q. Chen, M.K. La Peyre, K. Hu, and J.F. La Peyre, 2017: Predicting the impacts of Mississippi River diversions and sea-level rise on spatial patterns of eastern oyster growth rate and production. *Ecological Modelling*, **352**, 40–53. https://doi.org/10.1016/j.ecolmodel.2017.02.028

44. Macreadie, P.I., M.D.P. Costa, T.B. Atwood, D.A. Friess, J.J. Kelleway, H. Kennedy, C.E. Lovelock, O. Serrano, and C.M. Duarte, 2021: Blue carbon as a natural climate solution. *Nature Reviews Earth & Environment*, **2** (12), 826–839. https://doi.org/10.1038/s43017-021-00224-1

45. Prouty, N.G., A. Cohen, K.K. Yates, C.D. Storlazzi, P.W. Swarzenski, and D. White, 2017: Vulnerability of coral reefs to bioerosion from land-based source of pollution. *Journal of Geophysical Research Oceans*, **122** (12), 9319–9331. https://doi.org/10.1002/2017jc013264

46. Armstrong, C.W., G.K. Vondolia, N.S. Foley, L.-A. Henry, K. Needham, and A. Ressurreição, 2019: Expert assessment of risks posed by climate change and anthropogenic activities to ecosystem services in the deep North Atlantic. *Frontiers in Marine Science*, **6**, 158. https://doi.org/10.3389/fmars.2019.00158

47. Prouty, N.G., E.B. Roark, A.E. Koenig, A.W.J. Demopoulos, F.C. Batista, B.D. Kocar, D. Selby, M.D. McCarthy, F. Mienis, and S.W. Ross, 2014: Deep-sea coral record of human impact on watershed quality in the Mississippi River Basin. *Global Biogeochemical Cycles*, **28** (1), 29–43. https://doi.org/10.1002/2013GB004754

48. Levin, L.A., 2021: IPCC and the deep sea: A case for deeper knowledge. *Frontiers in Climate*, **3**, 720755. https://doi.org/10.3389/fclim.2021.720755

49. Levin, L.A. and N. Le Bris, 2015: The deep ocean under climate change. *Science*, **350** (6262), 766–768. https://doi.org/10.1126/science.aad0126

50. Sweetman, A.K., A.R. Thurber, C.R. Smith, L.A. Levin, C. Mora, C.-L. Wei, A.J. Gooday, D.O.B. Jones, M. Rex, M. Yasuhara, J. Ingels, H.A. Ruhl, C.A. Frieder, R. Danovaro, L. Würzberg, A. Baco, B.M. Grupe, A. Pasulka, K.S. Meyer, K.M. Dunlop, L.-A. Henry, and J.M. Roberts, 2017: Major impacts of climate change on deep-sea benthic ecosystems. *Elementa: Science of the Anthropocene*, **5**, 4. https://doi.org/10.1525/elementa.203

51. Hilmi, N., R. Chami, M.D. Sutherland, J.M. Hall-Spencer, L. Lebleu, M.B. Benitez, and L.A. Levin, 2021: The role of blue carbon in climate change mitigation and carbon stock conservation. *Frontiers in Climate*, **3**, 710546. https://doi.org/10.3389/fclim.2021.710546

52. Burge, C.A., C.M. Eakin, C.S. Friedman, B. Froelich, P.K. Hershberger, E.E. Hofmann, L.E. Petes, K.C. Prager, E. Weil, B.L. Willis, S.E. Ford, and C.D. Harvell, 2014: Climate change influences on marine infectious diseases: Implications for management and society. *Annual Review of Marine Science*, **6** (1), 249–277. https://doi.org/10.1146/annurev-marine-010213-135029

53. Heil, C.A. and A.L. Muni-Morgan, 2021: Florida's harmful algal bloom (HAB) problem: Escalating risks to human, environmental and economic health with climate change. *Frontiers in Ecology and Evolution*, **9**, 646080. https://doi.org/10.3389/fevo.2021.646080

54. Huntington, H.P., A. Zagorsky, B.P. Kaltenborn, H.C. Shin, J. Dawson, M. Lukin, P.E. Dahl, P. Guo, and D.N. Thomas, 2022: Societal implications of a changing Arctic Ocean. *Ambio*, **51** (2), 298–306. https://doi.org/10.1007/s13280-021-01601-2

55. Ritzman, J., A. Brodbeck, S. Brostrom, S. McGrew, S. Dreyer, T. Klinger, and S.K. Moore, 2018: Economic and sociocultural impacts of fisheries closures in two fishing-dependent communities following the massive 2015 U.S. West Coast harmful algal bloom. *Harmful Algae*, **80**, 35–45. https://doi.org/10.1016/j.hal.2018.09.002

56. Green, K.M., J.C. Selgrath, T.H. Frawley, W.K. Oestreich, E.J. Mansfield, J. Urteaga, S.S. Swanson, F.N. Santana, S.J. Green, J. Naggea, and L.B. Crowder, 2021: How adaptive capacity shapes the Adapt, React, Cope response to climate impacts: Insights from small-scale fisheries. *Climatic Change*, **164** (1), 15. https://doi.org/10.1007/s10584-021-02965-w

57. Hauser, D.D.W., A.V. Whiting, A.R. Mahoney, J. Goodwin, C. Harris, R.J. Schaeffer, R. Schaeffer, N.J.M. Laxague, A. Subramaniam, C.R. Witte, S. Betcher, J.M. Lindsay, and C.J. Zappa, 2021: Co-production of knowledge reveals loss of Indigenous hunting opportunities in the face of accelerating Arctic climate change. *Environmental Research Letters*, **16** (9), 095003. https://doi.org/10.1088/1748-9326/ac1a36

58. Huntington, H.P., S.L. Danielson, F.K. Wiese, M. Baker, P. Boveng, J.J. Citta, A. De Robertis, D.M.S. Dickson, E. Farley, J.C. George, K. Iken, D.G. Kimmel, K. Kuletz, C. Ladd, R. Levine, L. Quakenbush, P. Stabeno, K.M. Stafford, D. Stockwell, and C. Wilson, 2020: Evidence suggests potential transformation of the Pacific Arctic ecosystem is underway. *Nature Climate Change*, **10** (4), 342–348. https://doi.org/10.1038/s41558-020-0695-2

59. Lefebvre, K.A., E. Fachon, E.K. Bowers, D.G. Kimmel, J.A. Snyder, R. Stimmelmayr, J.M. Grebmeier, S. Kibler, D. Ransom Hardison, D.M. Anderson, D. Kulis, J. Murphy, J.C. Gann, D. Cooper, L.B. Eisner, J.T. Duffy-Anderson, G. Sheffield, R.S. Pickart, A. Mounsey, M.L. Willis, P. Stabeno, and E. Siddon, 2022: Paralytic shellfish toxins in Alaskan Arctic food webs during the anomalously warm ocean conditions of 2019 and estimated toxin doses to Pacific walruses and bowhead whales. *Harmful Algae*, **114**, 102205. https://doi.org/10.1016/j.hal.2022.102205

60. Lefebvre, K.A., L. Quakenbush, E. Frame, K. Burek, G. Sheffield, R. Stimmelmayr, A. Bryan, P. Kendrick, H. Ziel, T. Goldstein, J.A. Snyder, T. Gelatt, F. Gulland, B. Dickerson, and V. Gill, 2016: Prevalence of algal toxins in Alaskan marine mammals foraging in a changing arctic and subarctic environment. *Harmful Algae*, **55**, 13–24. https://doi.org/10.1016/j.hal.2016.01.007

61. McCabe, R.M., B.M. Hickey, R.M. Kudela, K.A. Lefebvre, N.G. Adams, B.D. Bill, F.M.D. Gulland, R.E. Thomson, W.P. Cochlan, and V.L. Trainer, 2016: An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. *Geophysical Research Letters*, **43** (19), 10366–10376. https://doi.org/10.1002/2016gl070023

62. Scaggs, S.A., D. Gerkey, and K.R. McLaughlin, 2021: Linking subsistence harvest diversity and productivity to adaptive capacity in an Alaskan food sharing network. *American Journal of Human Biology*, **33** (4), e23573. https://doi.org/10.1002/ajhb.23573

63. Huntington, H.P., L.T. Quakenbush, and M. Nelson, 2017: Evaluating the effects of climate change on indigenous marine mammal hunting in northern and western Alaska using traditional knowledge. *Frontiers in Marine Science*, **4**, 319. https://doi.org/10.3389/fmars.2017.00319

64. Scyphers, S.B., J.S. Picou, and J.H. Grabowski, 2019: Chronic social disruption following a systemic fishery failure. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (46), 22912–22914. https://doi.org/10.1073/pnas.1913914116

65. Slats, R., C. Oliver, R. Bahnke, H. Bell, A. Miller, D. Pungowiyi, J. Merculief, N. Menadelook Sr., J. Ivanoff, and C. Oxereok, 2019: Voices from the Front Lines of a Changing Bering Sea: An Indigenous Perspective for the 2019 Arctic Report Card. NOAA Arctic Report Card, Druckenmiller, M.L., R. Daniel, and M. Johnson, Eds. National Oceanic and Atmospheric Administration, Arctic Research Program, 88–99 pp. https://arctic.noaa.gov/report-card/report-card-2019/voices-from-the-front-lines-of-a-changing-bering-sea/

66. Tremblay, R., M. Landry-Cuerrier, and M.M. Humphries, 2020: Culture and the social-ecology of local food use by Indigenous communities in northern North America. *Ecology and Society*, **25** (2), 8. https://doi.org/10.5751/es-11542-250208

67. Jacox, M.G., M.A. Alexander, S.J. Bograd, and J.D. Scott, 2020: Thermal displacement by marine heatwaves. *Nature*, **584** (7819), 82–86. https://doi.org/10.1038/s41586-020-2534-z

68. Huntington, H.P., J. Raymond-Yakoubian, G. Noongwook, N. Naylor, C. Harris, Q. Harcharek, and B. Adams, 2021: "We never get stuck:" A collaborative analysis of change and coastal community subsistence practices in the Northern Bering and Chukchi Seas, Alaska. *Arctic*, **74** (2), 113–126. https://doi.org/10.14430/arctic72446

69. Pershing, A., K. Mills, A. Dayton, B. Franklin, and B. Kennedy, 2018: Evidence for adaptation from the 2016 marine heatwave in the Northwest Atlantic Ocean. *Oceanography*, **31** (2), 152–161. https://doi.org/10.5670/oceanog.2018.213

70. Samhouri, J.F., B.E. Feist, M.C. Fisher, O. Liu, S.M. Woodman, B. Abrahms, K.A. Forney, E.L. Hazen, D. Lawson, J. Redfern, and L.E. Saez, 2021: Marine heatwave challenges solutions to human-wildlife conflict. *Proceedings of the Royal Society B: Biological Sciences*, **288** (1964), 20211607. https://doi.org/10.1098/rspb.2021.1607

71. Bograd, S.J., M.G. Jacox, E.L. Hazen, E. Lovecchio, I. Montes, M. Pozo Buil, L.J. Shannon, W.J. Sydeman, and R.R. Rykaczewski, 2023: Climate change impacts on eastern boundary upwelling systems. *Annual Review of Marine Science*, **15** (1), 303–328. https://doi.org/10.1146/annurev-marine-032122-021945

72. Hodapp, D., I.T. Roca, D. Fiorentino, C. Garilao, K. Kaschner, K. Kesner-Reyes, B. Schneider, J. Segschneider, Á.T. Kocsis, W. Kiessling, T. Brey, and R. Froese, 2023: Climate change disrupts core habitats of marine species. *Global Change Biology*, **29** (12), 3304–3317. https://doi.org/10.1111/gcb.16612

73. Sheahan, M., C.A. Gould, J.E. Neumann, P.L. Kinney, S. Hoffmann, C. Fant, X. Wang, and M. Kolian, 2022: Examining the relationship between climate change and vibriosis in the United States: Projected health and economic impacts for the 21st century. *Environmental Health Perspectives*, **130** (8), 087007. https://doi.org/10.1289/ehp9999a

74. Tester, P.A., R.W. Litaker, and E. Berdalet, 2020: Climate change and harmful benthic microalgae. *Harmful Algae*, **91**, 101655. https://doi.org/10.1016/j.hal.2019.101655

75. Tittensor, D.P., C. Novaglio, C.S. Harrison, R.F. Heneghan, N. Barrier, D. Bianchi, L. Bopp, A. Bryndum-Buchholz, G.L. Britten, M. Büchner, W.W.L. Cheung, V. Christensen, M. Coll, J.P. Dunne, T.D. Eddy, J.D. Everett, J.A. Fernandes-Salvador, E.A. Fulton, E.D. Galbraith, D. Gascuel, J. Guiet, J.G. John, J.S. Link, H.K. Lotze, O. Maury, K. Ortega-Cisneros, J. Palacios-Abrantes, C.M. Petrik, H. du Pontavice, J. Rault, A.J. Richardson, L. Shannon, Y.-J. Shin, J. Steenbeek, C.A. Stock, and J.L. Blanchard, 2021: Next-generation ensemble projections reveal higher climate risks for marine ecosystems. *Nature Climate Change*, **11** (11), 973–981. https://doi.org/10.1038/s41558-021-01173-9

76. Heinze, C., T. Blenckner, H. Martins, D. Rusiecka, R. Döscher, M. Gehlen, N. Gruber, E. Holland, Ø. Hov, F. Joos, J.B.R. Matthews, R. Rødven, and S. Wilson, 2021: The quiet crossing of ocean tipping points. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (9), e2008478118. https://doi.org/10.1073/pnas.2008478118

77. Hoegh-Guldberg, O., L. Pendleton, and A. Kaup, 2019: People and the changing nature of coral reefs. *Regional Studies in Marine Science*, **30**, 100699. https://doi.org/10.1016/j.rsma.2019.100699

78. Penn, J.L. and C. Deutsch, 2022: Avoiding ocean mass extinction from climate warming. *Science*, **376** (6592), 524–526. https://doi.org/10.1126/science.abe9039

79. Stewart-Sinclair, P.J., K.S. Last, B.L. Payne, and T.A. Wilding, 2020: A global assessment of the vulnerability of shellfish aquaculture to climate change and ocean acidification. *Ecology and Evolution*, **10** (7), 3518–3534. https://doi.org/10.1002/ece3.6149

80. Dubik, B.A., E.C. Clark, T. Young, S.B.J. Zigler, M.M. Provost, M.L. Pinsky, and K. St. Martin, 2019: Governing fisheries in the face of change: Social responses to long-term geographic shifts in a U.S. fishery. *Marine Policy*, **99**, 243–251. https://doi.org/10.1016/j.marpol.2018.10.032

81. Cucuzza, M.L., H.L. Sagar, and R.B. Griffis, 2021: Synthesis of Public Comments to NOAA on Executive Order 14008, Tackling the Climate Crisis at Home and Abroad, Section 216(c): Recommendations on How to Make Fisheries and Protected Resources, Including Aquaculture, More Resilient to Climate Change. NOAA Technical Memorandum NMFS-F/SPO-218. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, 79 pp. https://spo.nmfs.noaa.gov/content/tech-memo/synthesis-public-comments-noaa-executive-order-14008-tackling-climate-crisis-home

82. Jacox, M.G., M.A. Alexander, N.J. Mantua, J.D. Scott, G. Hervieux, R.S. Webb, and F.E. Werner, 2018: Forcing of multiyear extreme ocean temperatures that impacted California Current living marine resources in 2016. *Bulletin of the American Meteorological Society*, **99** (1), S27–S33. https://doi.org/10.1175/bams-d-17-0119.1

83. Santora, J.A., N.J. Mantua, I.D. Schroeder, J.C. Field, E.L. Hazen, S.J. Bograd, W.J. Sydeman, B.K. Wells, J. Calambokidis, L. Saez, D. Lawson, and K.A. Forney, 2020: Habitat compression and ecosystem shifts as potential links between marine heatwave and record whale entanglements. *Nature Communications*, **11** (1), 536. https://doi.org/10.1038/s41467-019-14215-w

84. Ryan, J.P., R.M. Kudela, J.M. Birch, M. Blum, H.A. Bowers, F.P. Chavez, G.J. Doucette, K. Hayashi, R. Marin III, C.M. Mikulski, J.T. Pennington, C.A. Scholin, G.J. Smith, A. Woods, and Y. Zhang, 2017: Causality of an extreme harmful algal bloom in Monterey Bay, California, during the 2014–2016 northeast Pacific warm anomaly. *Geophysical Research Letters*, **44** (11), 5571–5579. https://doi.org/10.1002/2017gl072637

85. Fisher, M.C., S.K. Moore, S.L. Jardine, J.R. Watson, and J.F. Samhouri, 2021: Climate shock effects and mediation in fisheries. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (2), e2014379117. https://doi.org/10.1073/pnas.2014379117

86. Jardine, S.L., M.C. Fisher, S.K. Moore, and J.F. Samhouri, 2020: Inequality in the economic impacts from climate shocks in fisheries: The case of harmful algal blooms. *Ecological Economics*, **176**, 106691. https://doi.org/10.1016/j.ecolecon.2020.106691

87. Smith, J.A., M. Pozo Buil, J. Fiechter, D. Tommasi, and M.G. Jacox, 2022: Projected novelty in the climate envelope of the California Current at multiple spatial-temporal scales. *PLoS Climate*, **1** (4), e0000022. https://doi.org/10.1371/journal.pclm.0000022

88. Pershing, A.J., N.R. Record, B.S. Franklin, B.T. Kennedy, L. McClenachan, K.E. Mills, J.D. Scott, A.C. Thomas, and N.H. Wolff, 2019: Challenges to natural and human communities from surprising ocean temperatures. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (37), 18378–18383. https://doi.org/10.1073/pnas.1901084116

89. OCM, 2022: Digital Coasts. National Oceanic and Atmospheric Administration, National Ocean Service, Office for Coastal Management. https://coast.noaa.gov/digitalcoast/

90. Cheung, W.W.L. and T.L. Frölicher, 2020: Marine heatwaves exacerbate climate change impacts for fisheries in the northeast Pacific. *Scientific Reports*, **10** (1), 6678. https://doi.org/10.1038/s41598-020-63650-z

91. Smale, D.A., T. Wernberg, E.C.J. Oliver, M. Thomsen, B.P. Harvey, S.C. Straub, M.T. Burrows, L.V. Alexander, J.A. Benthuysen, M.G. Donat, M. Feng, A.J. Hobday, N.J. Holbrook, S.E. Perkins-Kirkpatrick, H.A. Scannell, A. Sen Gupta, B.L. Payne, and P.J. Moore, 2019: Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nature Climate Change*, **9** (4), 306–312. https://doi.org/10.1038/s41558-019-0412-1

92. Lam, V.W.Y., W.W.L. Cheung, G. Reygondeau, and U.R. Sumaila, 2016: Projected change in global fisheries revenues under climate change. *Scientific Reports*, **6** (1), 1–8. https://doi.org/10.1038/srep32607

93. Sumaila, U.R., T.C. Tai, V.W.Y. Lam, W.W.L. Cheung, M. Bailey, A.M. Cisneros-Montemayor, O.L. Chen, and S.S. Gulati, 2019: Benefits of the Paris Agreement to ocean life, economies, and people. *Science Advances*, **5** (2), 3855. https://doi.org/10.1126/sciadv.aau3855

94. Bhattachan, A., M.D. Jurjonas, A.C. Moody, P.R. Morris, G.M. Sanchez, L.S. Smart, P.J. Taillie, R.E. Emanuel, and E.L. Seekamp, 2018: Sea level rise impacts on rural coastal social-ecological systems and the implications for decision making. *Environmental Science & Policy*, **90**, 122–134. https://doi.org/10.1016/j.envsci.2018.10.006

95. Jurjonas, M. and E. Seekamp, 2018: Rural coastal community resilience: Assessing a framework in eastern North Carolina. *Ocean & Coastal Management*, **162**, 137–150. https://doi.org/10.1016/j.ocecoaman.2017.10.010

96. Bell, R.J., J. Odell, G. Kirchner, and S. Lomonico, 2020: Actions to promote and achieve climate-ready fisheries: Summary of current practice. *Marine and Coastal Fisheries*, **12** (3), 166–190. https://doi.org/10.1002/mcf2.10112

97. Watson, J.T. and A.C. Haynie, 2018: Paths to resilience: The walleye pollock fleet uses multiple fishing strategies to buffer against environmental change in the Bering Sea. *Canadian Journal of Fisheries and Aquatic Sciences*, **75** (11), 1977–1989. https://doi.org/10.1139/cjfas-2017-0315

98. Fedewa, E.J., T.M. Jackson, J.I. Richar, J.L. Gardner, and M.A. Litzow, 2020: Recent shifts in northern Bering Sea snow crab (*Chionoecetes opilio*) size structure and the potential role of climate-mediated range contraction. *Deep Sea Research Part II: Topical Studies in Oceanography*, **181–182**, 104878. https://doi.org/10.1016/j.dsr2.2020.104878

99. Jones, M.C., M. Berkelhammer, K.J. Keller, K. Yoshimura, and M.J. Wooller, 2020: High sensitivity of Bering Sea winter sea ice to winter insolation and carbon dioxide over the last 5500 years. *Science Advances*, **6** (36). https://doi.org/10.1126/sciadv.aaz9588

100. Spies, I., K.M. Gruenthal, D.P. Drinan, A.B. Hollowed, D.E. Stevenson, C.M. Tarpey, and L. Hauser, 2020: Genetic evidence of a northward range expansion in the eastern Bering Sea stock of Pacific cod. *Evolutionary Applications*, **13** (2), 362–375. https://doi.org/10.1111/eva.12874

101. Stevenson, D.E. and R.R. Lauth, 2019: Bottom trawl surveys in the northern Bering Sea indicate recent shifts in the distribution of marine species. *Polar Biology*, **42** (2), 407–421. https://doi.org/10.1007/s00300-018-2431-1

102. Szuwalski, C., 2022: An Assessment for Eastern Bering Sea Snow Crab. North Pacific Fishery Management Council, Anchorage, AK. https://meetings.npfmc.org/commentreview/downloadfile?p=fca55335-ad34-4896-9b1e-4c09aa8342ce.pdf&filename=ebs%20snow%20safe%20final.pdf

103. Whitmore, K., A. Richards, J. Carloni, M. Hunter, M. Hawk, and K. Drew, 2013: Assessment Report for Gulf of Maine Northern Shrimp—2013. Atlantic States Marine Fisheries Commission, Arlington, VA, 86 pp. http://www.asmfc.org/species/northern-shrimp

104. Bellquist, L., V. Saccomanno, B.X. Semmens, M. Gleason, and J. Wilson, 2021: The rise in climate change-induced federal fishery disasters in the United States. *PeerJ*, **9**, e11186. https://doi.org/10.7717/peerj.11186

105. Barbeaux, S.J., K. Holsman, and S. Zador, 2020: Marine heatwave stress test of ecosystem-based fisheries management in the Gulf of Alaska Pacific cod fishery. *Frontiers in Marine Science*, **7**, 703. https://doi.org/10.3389/fmars.2020.00703

106. Pershing, A.J., M.A. Alexander, C.M. Hernandez, L.A. Kerr, A. Le Bris, K.E. Mills, J.A. Nye, N.R. Record, H.A. Scannell, J.D. Scott, G.D. Sherwood, and A.C. Thomas, 2015: Slow adaptation in the face of rapid warming leads to collapse of the Gulf of Maine cod fishery. *Science*, **350** (6262), 809–812. https://doi.org/10.1126/science.aac9819

107. Chasco, B.E., M.E. Hunsicker, K.C. Jacobson, O.T. Welch, C.A. Morgan, B.A. Muhling, and J.A. Harding, 2022: Evidence of temperature-driven shifts in market squid *Doryteuthis opalescens* densities and distribution in the California Current ecosystem. *Marine and Coastal Fisheries*, **14** (1), e10190. https://doi.org/10.1002/mcf2.10190

108. Goethel, D.R., D.H. Hanselman, C.J. Rodgveller, K.H. Fenske, S.K. Shotwell, K.B. Echave, P.W. Malecha, K.A. Siwicke, and C.R. Lunsford, 2020: Assessment of the Sablefish Stock in Alaska. NPFMC Bering Sea, Aleutian Islands and Gulf of Alaska SAFE. https://apps-afsc.fisheries.noaa.gov/refm/docs/2020/sablefish.pdf

109. Hollowed, A.B., K.K. Holsman, A.C. Haynie, A.J. Hermann, A.E. Punt, K. Aydin, J.N. Ianelli, S. Kasperski, W. Cheng, A. Faig, K.A. Kearney, J.C.P. Reum, P. Spencer, I. Spies, W. Stockhausen, C.S. Szuwalski, G.A. Whitehouse, and T.K. Wilderbuer, 2020: Integrated modeling to evaluate climate change impacts on coupled social-ecological systems in Alaska. *Frontiers in Marine Science*, **6**, 775. https://doi.org/10.3389/fmars.2019.00775

110. Holsman, K.K., A.C. Haynie, A.B. Hollowed, J.C.P. Reum, K. Aydin, A.J. Hermann, W. Cheng, A. Faig, J.N. Ianelli, K.A. Kearney, and A.E. Punt, 2020: Ecosystem-based fisheries management forestalls climate-driven collapse. *Nature Communications*, **11** (1), 4579. https://doi.org/10.1038/s41467-020-18300-3

111. Rheuban, J.E., M.T. Kavanaugh, and S.C. Doney, 2017: Implications of future northwest Atlantic bottom temperatures on the American lobster (*Homarus americanus*) fishery. *Journal of Geophysical Research: Oceans*, **122** (12), 9387–9398. https://doi.org/10.1002/2017jc012949

112. Szuwalski, C., W. Cheng, R. Foy, A.J. Hermann, A. Hollowed, K. Holsman, J. Lee, W. Stockhausen, and J. Zheng, 2021: Climate change and the future productivity and distribution of crab in the Bering Sea. *ICES Journal of Marine Science*, **78** (2), 502–515. https://doi.org/10.1093/icesjms/fsaa140

113. Moore, C., J.W. Morley, B. Morrison, M. Kolian, E. Horsch, T. Frölicher, M.L. Pinsky, and R. Griffis, 2021: Estimating the economic impacts of climate change on 16 major US fisheries. *Climate Change Economics*, **12** (1), 2150002. https://doi.org/10.1142/s2010007821500020

114. Hanich, Q., C.C.C. Wabnitz, Y. Ota, M. Amos, C. Donato-Hunt, and A. Hunt, 2018: Small-scale fisheries under climate change in the Pacific Islands region. *Marine Policy*, **88**, 279–284. https://doi.org/10.1016/j.marpol.2017.11.011

115. Ojea, E., I. Pearlman, S.D. Gaines, and S.E. Lester, 2017: Fisheries regulatory regimes and resilience to climate change. *Ambio*, **46** (4), 399–412. https://doi.org/10.1007/s13280-016-0850-1

116. Palacios-Abrantes, J., T.L. Frölicher, G. Reygondeau, U.R. Sumaila, A. Tagliabue, Colette C.C. Wabnitz, and William W.L. Cheung, 2022: Timing and magnitude of climate-driven range shifts in transboundary fish stocks challenge their management. *Global Change Biology*, **28** (7), 2312–2326. https://doi.org/10.1111/gcb.16058

117. Pinsky, M.L., G. Reygondeau, R. Caddell, J. Palacios-Abrantes, J. Spijkers, and W.W.L. Cheung, 2018: Preparing ocean governance for species on the move. *Science*, **360** (6394), 1189–1191. https://doi.org/10.1126/science.aat2360

118. Young, T., E.C. Fuller, M.M. Provost, K.E. Coleman, K. St. Martin, B.J. McCay, and M.L. Pinsky, 2019: Adaptation strategies of coastal fishing communities as species shift poleward. *ICES Journal of Marine Science*, **76** (1), 93–103. https://doi.org/10.1093/icesjms/fsy140

119. Sainsbury, N.C., M.J. Genner, G.R. Saville, J.K. Pinnegar, C.K. O'Neill, S.D. Simpson, and R.A. Turner, 2018: Changing storminess and global capture fisheries. *Nature Climate Change*, **8** (8), 655–659. https://doi.org/10.1038/s41558-018-0206-x

120. NMFS, 2021: U.S. Seafood Industry and For-Hire Sector Impacts from COVID-19: 2020 in Perspective. NOAA Technical Memorandum NMFS-SPO-221. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, 88 pp. https://spo.nmfs.noaa.gov/sites/default/files/TM221.pdf

121. Cline, T.J., D.E. Schindler, and R. Hilborn, 2017: Fisheries portfolio diversification and turnover buffer Alaskan fishing communities from abrupt resource and market changes. *Nature Communications*, **8** (1), 14042. https://doi.org/10.1038/ncomms14042

122. Holsman, K.K., E.L. Hazen, A. Haynie, S. Gourguet, A. Hollowed, S.J. Bograd, J.F. Samhouri, and K. Aydin, 2019: Towards climate resiliency in fisheries management. *ICES Journal of Marine Science*, **76** (5), 1368–1378. https://doi.org/10.1093/icesjms/fsz031

123. Woods, P.J., J.I. Macdonald, H. Bárðarson, S. Bonanomi, W.J. Boonstra, G. Cornell, G. Cripps, R. Danielsen, L. Färber, A.S.A. Ferreira, K. Ferguson, M. Holma, R.E. Holt, K.L. Hunter, A. Kokkalis, T.J. Langbehn, G. Ljungström, E. Nieminen, M.C. Nordström, M. Oostdijk, A. Richter, G. Romagnoni, C. Sguotti, A. Simons, N.L. Shackell, M. Snickars, J.D. Whittington, H. Wootton, and J. Yletyinen, 2022: A review of adaptation options in fisheries management to support resilience and transition under socio-ecological change. *ICES Journal of Marine Science*, **79** (2), 463–479. https://doi.org/10.1093/icesjms/fsab146

124. Stoll, J.S., C.M. Beitl, and J.A. Wilson, 2016: How access to Maine's fisheries has changed over a quarter century: The cumulative effects of licensing on resilience. *Global Environmental Change*, **37**, 79–91. https://doi.org/10.1016/j.gloenvcha.2016.01.005

125. Catch Together, 2020: Pacific Coast Fisheries Diversification Framework. The Nature Conservancy, 77 pp. https://www.nature.org/content/dam/tnc/nature/en/documents/Port_Orford_Framework_Document_Final.pdf

126. Stoll, J.S., B.A. Dubik, and L.M. Campbell, 2015: Local seafood: Rethinking the direct marketing paradigm. *Ecology and Society*, **20** (2), 40. https://doi.org/10.5751/es-07686-200240

127. Hazen, E.L., K.L. Scales, S.M. Maxwell, D.K. Briscoe, H. Welch, S.J. Bograd, H. Bailey, S.R. Benson, T. Eguchi, H. Dewar, S. Kohin, D.P. Costa, L.B. Crowder, and R.L. Lewison, 2018: A dynamic ocean management tool to reduce bycatch and support sustainable fisheries. *Science Advances*, **4** (5), 3001. https://doi.org/10.1126/sciadv.aar3001

128. Collie, J.S., R.J. Bell, S.B. Collie, and C. Minto, 2021: Harvest strategies for climate-resilient fisheries. *ICES Journal of Marine Science*, **78** (8), 2774–2783. https://doi.org/10.1093/icesjms/fsab152

129. Northrop, E., P. Schuhmann, L. Burke, A. Fyall, S. Alvarez, A. Spenceley, S. Becken, K. Kato, J. Roy, S. Some, J. Veitayaki, A. Markandya, I. Galarraga, P. Greño, I. Ruiz-Gauna, M. Curnock, M.E. Wood, M.Y. Yin, S. Riedmiller, E. Carter, R. Haryanto, E. Holloway, R. Croes, J. Ridderstaat, and M. Godovykh, 2022: Opportunities for Transforming Coastal and Marine Tourism: Towards Sustainability, Regeneration and Resilience. World Resources Institute, Washington, DC. https://oceanpanel.org/publication/opportunities-for-transforming-coastal-and-marine-tourism-towards-sustainability-regeneration-and-resilience/

130. Reineman, D.R., L.N. Thomas, and M.R. Caldwell, 2017: Using local knowledge to project sea level rise impacts on wave resources in California. *Ocean & Coastal Management*, **138**, 181–191. https://doi.org/10.1016/j.ocecoaman.2017.01.020

131. Hallegraeff, G.M., D.M. Anderson, C. Belin, M.-Y.D. Bottein, E. Bresnan, M. Chinain, H. Enevoldsen, M. Iwataki, B. Karlson, C.H. McKenzie, I. Sunesen, G.C. Pitcher, P. Provoost, A. Richardson, L. Schweibold, P.A. Tester, V.L. Trainer, A.T. Yñiguez, and A. Zingone, 2021: Perceived global increase in algal blooms is attributable to intensified monitoring and emerging bloom impacts. *Communications Earth & Environment*, **2** (1), 117. https://doi.org/10.1038/s43247-021-00178-8

132. Wang, M., C. Hu, B.B. Barnes, G. Mitchum, B. Lapointe, and J.P. Montoya, 2019: The great Atlantic *Sargassum* belt. *Science*, **365** (6448), 83–87. https://doi.org/10.1126/science.aaw7912

133. Bechard, A., 2020: Harmful algal blooms and tourism: The economic impact to counties in southwest Florida. *Review of Regional Studies*, **50** (2), 170–188. https://doi.org/10.52324/001c.12705

134. Burrowes, R., C. Wabnitz, and J. Eyzaguirre, 2019: The Great Sargassum Disaster of 2018. ESSA Technologies. https://www.essa.com/the-great-sargassum-disaster-of-2018/

135. Townhill, B.L., Z. Radford, G. Pecl, I. van Putten, J.K. Pinnegar, and K. Hyder, 2019: Marine recreational fishing and the implications of climate change. *Fish and Fisheries*, **20** (5), 977–992. https://doi.org/10.1111/faf.12392

136. Dundas, S.J. and R.H. von Haefen, 2020: The effects of weather on recreational fishing demand and adaptation: Implications for a changing climate. *Journal of the Association of Environmental and Resource Economists*, **7** (2), 209–242. https://doi.org/10.1086/706343

137. Palma, D., A. Varnajot, K. Dalen, I.K. Basaran, C. Brunette, M. Bystrowska, A.D. Korablina, R.C. Nowicki, and T.A. Ronge, 2019: Cruising the marginal ice zone: Climate change and Arctic tourism. *Polar Geography*, **42** (4), 215–235. https://doi.org/10.1080/1088937x.2019.1648585

138. Spalding, M., L. Burke, S.A. Wood, J. Ashpole, J. Hutchison, and P. zu Ermgassen, 2017: Mapping the global value and distribution of coral reef tourism. *Marine Policy*, **82**, 104–113. https://doi.org/10.1016/j.marpol.2017.05.014

139. Van Deren, M., J. Mojica, J. Martin, C. Armistead, and C. Koefod, 2019: The Whales in Our Waters: The Economic Benefits of Whale Watching in San Juan County. Earth Economics, Tacoma, WA. https://www.eartheconomics.org/srkw

140. Dawson, J., L. Pizzolato, S.E.L. Howell, L. Copland, and M.E. Johnston, 2018: Temporal and spatial patterns of ship traffic in the Canadian Arctic from 1990 to 2015. *Journal of The Arctic Institute of North America*, **71** (1). https://doi.org/10.14430/arctic4698

141. Li, X., S.R. Stephenson, A.H. Lynch, M.A. Goldstein, D.A. Bailey, and S. Veland, 2021: Arctic shipping guidance from the CMIP6 ensemble on operational and infrastructural timescales. *Climatic Change*, **167** (1), 23. https://doi.org/10.1007/s10584-021-03172-3

142. CRS, 2023: Changes in the Arctic: Background and Issues for Congress. CRS Report R41153. Congressional Research Service. https://crsreports.congress.gov/product/pdf/r/r41153

143. Mudryk, L.R., J. Dawson, S.E.L. Howell, C. Derksen, T.A. Zagon, and M. Brady, 2021: Impact of 1, 2 and 4 °C of global warming on ship navigation in the Canadian Arctic. *Nature Climate Change*, **11** (8), 673–679. https://doi.org/10.1038/s41558-021-01087-6

144. Arrigo, K.R., G.L. van Dijken, M.A. Cameron, J. van der Grient, L.M. Wedding, L. Hazen, J. Leape, G. Leonard, A. Merkl, F. Micheli, M.M. Mills, S. Monismith, N.T. Ouellette, A. Zivian, M. Levi, and R.M. Bailey, 2020: Synergistic interactions among growing stressors increase risk to an Arctic ecosystem. *Nature Communications*, **11** (1), 6255. https://doi.org/10.1038/s41467-020-19899-z

145. Ivanova, S.V., S.T. Kessel, M. Espinoza, M.F. McLean, C. O'Neill, J. Landry, N.E. Hussey, R. Williams, S. Vagle, and A.T. Fisk, 2020: Shipping alters the movement and behavior of Arctic cod (*Boreogadus saida*), a keystone fish in Arctic marine ecosystems. *Ecological Applications*, **30** (3), e02050. https://doi.org/10.1002/eap.2050

146. Zhang, Q., Z. Wan, B. Hemmings, and F. Abbasov, 2019: Reducing black carbon emissions from Arctic shipping: Solutions and policy implications. *Journal of Cleaner Production*, **241**, 118261. https://doi.org/10.1016/j.jclepro.2019.118261

147. IMO, 2020: Fourth Greenhouse Gas Study 2020. International Maritime Organization, London, UK. https://www.imo.org/en/ourwork/environment/pages/fourth-imo-greenhouse-gas-study-2020.aspx

148. EPA, 2023: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2021. EPA 430-R-23-002. U.S. Environmental Protection Agency. https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021

149. Daniel, H., J.P.F. Trovão, and D. Williams, 2022: Shore power as a first step toward shipping decarbonization and related policy impact on a dry bulk cargo carrier. *eTransportation*, **11**, 100150. https://doi.org/10.1016/j.etran.2021.100150

150. GOV.UK, 2022: COP 26: Clydebank Declaration for Green Shipping Corridors. HM Government, Department for Transport. https://www.gov.uk/government/publications/cop-26-clydebank-declaration-for-green-shipping-corridors/cop-26-clydebank-declaration-for-green-shipping-corridors

151. Nichols, W. and R. Clisby, 2021: 40% of Oil and Gas Reserves Threatened by Climate Change. Verisk Maplecroft. https://www.maplecroft.com/insights/analysis/40-of-oil-and-gas-reserves-threatened-by-climate-change/

152. Burkett, V., 2011: Global climate change implications for coastal and offshore oil and gas development. *Energy Policy*, **39** (12), 7719–7725. https://doi.org/10.1016/j.enpol.2011.09.016

153. Casas-Prat, M. and X.L. Wang, 2020: Projections of extreme ocean waves in the Arctic and potential implications for coastal inundation and erosion. *Journal of Geophysical Research: Oceans*, **125** (8), e2019JC015745. https://doi.org/10.1029/2019jc015745

154. Dong, J., Z. Asif, Y. Shi, Y. Zhu, and Z. Chen, 2022: Climate change impacts on coastal and offshore petroleum infrastructure and the associated oil spill risk: A review. *Journal of Marine Science and Engineering*, **10** (7), 849. https://doi.org/10.3390/jmse10070849

155. Ebad Sichani, M., K.A. Anarde, K.M. Capshaw, J.E. Padgett, R.A. Meidl, P. Hassanzadeh, T.P. Loch-Temzelides, and P.B. Bedient, 2020: Hurricane risk assessment of petroleum infrastructure in a changing climate. *Frontiers in Built Environment*, **6**, 104. https://doi.org/10.3389/fbuil.2020.00104

156. The White House, 2021: Fact sheet: Biden administration jumpstarts offshore wind energy projects to create jobs. The White House, Washington, DC, March 29, 2021. https://www.whitehouse.gov/briefing-room/statements-releases/2021/03/29/fact-sheet-biden-administration-jumpstarts-offshore-wind-energy-projects-to-create-jobs/

157. BOEM, 2022: Outer Continental Shelf Renewable Energy Leases: Map Book. OREP-2022-2006. U.S. Department of the Interior, Bureau of Ocean Energy Management. https://www.boem.gov/sites/default/files/documents/renewable-energy/Leases-Map-Book-July%202022.pdf

158. Christopher, T.R., M. Goldstein, M. Williams, and A. Carter, 2022: The Road to 30 Gigawatts: Key Actions to Scale an Offshore Wind Industry in the United States. Center for American Progress. https://www.americanprogress.org/article/the-road-to-30-gigawatts-key-actions-to-scale-an-offshore-wind-industry-in-the-united-states/

159. Hogan, F., B. Hooker, B. Jensen, L. Johnston, A. Lipsky, E. Methratta, A. Silva, and A. Hawkins, 2023: Fisheries and Offshore Wind Interactions: Synthesis of Science. NOAA Technical Memorandum NMFS-NE-291. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northeast Fisheries Science Center, Woods Hole, MA. https://doi.org/10.25923/tcjt-3a69

160. Klain, S.C., T. Satterfield, S. MacDonald, N. Battista, and K.M.A. Chan, 2017: Will communities "open-up" to offshore wind? Lessons learned from New England islands in the United States. *Energy Research & Social Science*, **34**, 13–26. https://doi.org/10.1016/j.erss.2017.05.009

161. Methratta, E.T., A. Hawkins, B.R. Hooker, A. Lipsky, and J.A. Hare, 2020: Offshore wind development in the Northeast US Shelf Large Marine Ecosystem: Ecological, human, and fishery management dimensions. *Oceanography*, **33** (4), 16–27. https://doi.org/10.5670/oceanog.2020.402

162. Tyler, G., D. Bidwell, T. Smythe, and S. Trandafir, 2022: Preferences for community benefits for offshore wind development projects: A case study of the Outer Banks of North Carolina, U.S. *Journal of Environmental Policy & Planning*, **24** (1), 39–55. https://doi.org/10.1080/1523908x.2021.1940896

163. Koehn, L.E., L.K. Nelson, J.F. Samhouri, K.C. Norman, M.G. Jacox, A.C. Cullen, J. Fiechter, M. Pozo Buil, and P.S. Levin, 2022: Social-ecological vulnerability of fishing communities to climate change: A U.S. West Coast case study. *PLoS ONE*, **17** (8), e0272120. https://doi.org/10.1371/journal.pone.0272120

164. MAFMC, 2022: East Coast Climate Change Scenario Planning. Mid-Atlantic Fishery Management Council. https://www.mafmc.org/climate-change-scenario-planning

165. PFMC, 2022: Climate and Communities Initiative. Pacific Fishery Management Council. https://www.pcouncil.org/actions/climate-and-communities-initiative/

166. Cities of Portland and South Portland, 2021: One Climate Future: Charting a Course for Portland and South Portland. Portland and South Portland Sustainability Offices. https://www.oneclimatefuture.org/wp-content/uploads/2021/02/OneClimateFuture_FinalJan2021_Downsized.pdf

167. Takak, L., H. Shepherd, G. Griffith, and M. Hall, 2021: Norton Bay Watershed Ocean and Coastal Management Plan (NBWOCMP): Protecting the Watershed's Subsistence Culture and Resources. Norton Bay Inter-Tribal Watershed Council. https://www.nortonbaywatershed.org/wp-content/uploads/2022/01/Norton-Bay-Watershed-Ocean-and-Coastal-Management-Plan-NBWOCMP_8-25-21_FNLv3-merged.pdf

168. Gattuso, J.-P., A.K. Magnan, L. Bopp, W.W.L. Cheung, C.M. Duarte, J. Hinkel, E. Mcleod, F. Micheli, A. Oschlies, P. Williamson, R. Billé, V.I. Chalastani, R.D. Gates, J.-O. Irisson, J.J. Middelburg, H.-O. Pörtner, and G.H. Rau, 2018: Ocean solutions to address climate change and its effects on marine ecosystems. *Frontiers in Marine Science*, **5**, 337. https://doi.org/10.3389/fmars.2018.00337

169. Williamson, P. and J.-P. Gattuso, 2022: Carbon removal using coastal blue carbon ecosystems is uncertain and unreliable, with questionable climatic cost-effectiveness. *Frontiers in Climate*, **4**, 853666. https://doi.org/10.3389/fclim.2022.853666

170. ARPA-E, 2022: Direct Removal of Carbon Dioxide from Oceanwater. U.S. Department of Energy, Advanced Research Projects Agency–Energy, accessed May 26, 2022. https://arpa-e.energy.gov/technologies/exploratory-topics/direct-ocean-capture

171. Bertram, C. and C. Merk, 2020: Public perceptions of ocean-based carbon dioxide removal: The nature-engineering divide? *Frontiers in Climate*, **2**, 594194. https://doi.org/10.3389/fclim.2020.594194

172. National Academies of Sciences, Engineering, and Medicine, 2022: *A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration*. The National Academies Press, Washington, DC, 322 pp. https://doi.org/10.17226/26278

173. Silverman-Roati, K., M.B. Gerrard, and R.M. Webb, 2021: Removing Carbon Dioxide Through Seaweed Cultivation: Legal Challenges and Opportunities. Columbia Law School, Sabin Center for Climate Change Law. https://scholarship.law.columbia.edu/faculty_scholarship/2980

174. XPRIZE, 2022: $100M Prize for Carbon Removal. XPRIZE Foundation, accessed May 26, 2022. https://www.xprize.org/prizes/elonmusk

175. University of Hawai'i, 2021: $6M for UH wave energy conversion research. *University of Hawai◻i News*, August 11, 2021. https://www.hawaii.edu/news/2021/08/11/wave-energy-conversion-6m/

176. Hoegh-Guldberg, O., K. Caldeira, T. Chopin, S. Gaines, P. Haugan, M. Hemer, J. Howard, M. Konar, D. Krause-Jensen, E. Lindstad, C. Lovelock, M. Michelin, F. Nielsen, E. Northrop, R. Parker, J. Roy, T. Smith, S. Some, and P. Tyedmers, 2019: The Ocean as a Solution to Climate Change: Five Opportunities for Action. World Resources Institute, Washington, DC. https://oceanpanel.org/publication/the-ocean-as-a-solution-to-climate-change-five-opportunities-for-action/

177. Gephart, J.A., P.J.G. Henriksson, R.W.R. Parker, A. Shepon, K.D. Gorospe, K. Bergman, G. Eshel, C.D. Golden, B.S. Halpern, S. Hornborg, M. Jonell, M. Metian, K. Mifflin, R. Newton, P. Tyedmers, W. Zhang, F. Ziegler, and M. Troell, 2021: Environmental performance of blue foods. *Nature*, **597** (7876), 360–365. https://doi.org/10.1038/s41586-021-03889-2

178. UNEP, 2021: Emissions Gap Report 2021: The Heat Is On–A World of Climate Promises Not Yet Delivered. United Nations Environment Programme, Nairobi, Kenya. https://www.unep.org/emissions-gap-report-2021

179. IPCC, 2021: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2391 pp. https://doi.org/10.1017/9781009157896

180. Ellam Yua, J. Raymond-Yakoubian, R. Aluaq Daniel, and C. Behe, 2022: A framework for co-production of knowledge in the context of Arctic research. *Ecology and Society*, **27** (1), 34. https://doi.org/10.5751/es-12960-270134

181. Huntington, H.P., M. Carey, C. Apok, B.C. Forbes, S. Fox, L.K. Holm, A. Ivanova, J. Jaypoody, G. Noongwook, and F. Stammler, 2019: Climate change in context: Putting people first in the Arctic. *Regional Environmental Change*, **19** (4), 1217–1223. https://doi.org/10.1007/s10113-019-01478-8

182. Degroot, D., K. Anchukaitis, M. Bauch, J. Burnham, F. Carnegy, J. Cui, K. de Luna, P. Guzowski, G. Hambrecht, H. Huhtamaa, A. Izdebski, K. Kleemann, E. Moesswilde, N. Neupane, T. Newfield, Q. Pei, E. Xoplaki, and N. Zappia, 2021: Towards a rigorous understanding of societal responses to climate change. *Nature*, **591** (7851), 539–550. https://doi.org/10.1038/s41586-021-03190-2

183. Boström-Einarsson, L., R.C. Babcock, E. Bayraktarov, D. Ceccarelli, N. Cook, S.C.A. Ferse, B. Hancock, P. Harrison, M. Hein, E. Shaver, A. Smith, D. Suggett, P.J. Stewart-Sinclair, T. Vardi, and I.M. McLeod, 2020: Coral restoration–A systematic review of current methods, successes, failures and future directions. *PLoS ONE*, **15** (1), e0226631. https://doi.org/10.1371/journal.pone.0226631

184. Condie, S.A., K.R.N. Anthony, R.C. Babcock, M.E. Baird, R. Beeden, C.S. Fletcher, R. Gorton, D. Harrison, A.J. Hobday, É.E. Plagányi, and D.A. Westcott, 2021: Large-scale interventions may delay decline of the Great Barrier Reef. *Royal Society Open Science*, **8** (4), 201296. https://doi.org/10.1098/rsos.201296

185. Reguero, B.G., M.W. Beck, D.N. Bresch, J. Calil, and I. Meliane, 2018: Comparing the cost effectiveness of nature-based and coastal adaptation: A case study from the Gulf Coast of the United States. *PLoS ONE*, **13** (4), e0192132. https://doi.org/10.1371/journal.pone.0192132

186. Riisager-Simonsen, C., G. Fabi, L. van Hoof, N. Holmgren, G. Marino, and D. Lisbjerg, 2022: Marine nature-based solutions: Where societal challenges and ecosystem requirements meet the potential of our oceans. *Marine Policy*, **144**, 105198. https://doi.org/10.1016/j.marpol.2022.105198

187. Seddon, N., A. Chausson, P. Berry, C.A.J. Girardin, A. Smith, and B. Turner, 2020: Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375** (1794), 20190120. https://doi.org/10.1098/rstb.2019.0120

188. Bremer, L.L., B. Keeler, P. Pascua, R. Walker, and E. Sterling, 2021: Ch. 5. Nature-based solutions, sustainable development, and equity. In: *Nature-Based Solutions and Water Security*. Cassin, J., J.H. Matthews, and E.L. Gunn, Eds. Elsevier, 81–105. https://doi.org/10.1016/b978-0-12-819871-1.00016-6

189. Water Power Technologies Office, 2022: 2020–2021 Accomplishments Report. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Water Power Technologies Office. https://www.energy.gov/sites/default/files/2022-03/wpto-accomplishments-report-march-2022.pdf

190. Taylor, J., J.-M. Bonello, D. Baresic, and T. Smith, 2022: Future Maritime Fuels in the USA—The Options and Their Potential Pathways. UMAS, London, UK, 59 pp. https://oceanconservancy.org/wp-content/uploads/2022/04/oc_fuels_final_report_20220117.pdf

191. Cooley, S.R., S. Klinsky, D.R. Morrow, and T. Satterfield, 2023: Sociotechnical considerations about ocean carbon dioxide removal. *Annual Review of Marine Science*, **15** (1), 41–66. https://doi.org/10.1146/annurev-marine-032122-113850

192. Mooney, T.A., M.H. Andersson, and J. Stanley, 2020: Acoustic impacts of offshore wind energy on fishery resources: An evolving source and varied effects across a wind farm's lifetime. *Oceanography*, **33** (4), 82–95. https://doi.org/10.5670/oceanog.2020.408

193. Perry, R. and W. Heyman, 2020: Considerations for offshore wind energy development effects on fish and fisheries in the United States: A review of existing studies, new efforts, and opportunities for innovation. *Oceanography*, **33** (4), 28–37. https://doi.org/10.5670/oceanog.2020.403

194. Gardiner, S.M., 2006: A Perfect Moral Storm: Climate change, intergenerational ethics and the problem of moral corruption. *Environmental Values*, **15** (3), 397–413. https://doi.org/10.3197/096327106778226293

195. Haas, B., M. Mackay, C. Novaglio, L. Fullbrook, M. Murunga, C. Sbrocchi, J. McDonald, P.C. McCormack, K. Alexander, M. Fudge, L. Goldsworthy, F. Boschetti, I. Dutton, L. Dutra, J. McGee, Y. Rousseau, E. Spain, R. Stephenson, J. Vince, C. Wilcox, and M. Haward, 2022: The future of ocean governance. *Reviews in Fish Biology and Fisheries*, **32** (1), 253–270. https://doi.org/10.1007/s11160-020-09631-x

196. Brett, A., J. Leape, M. Abbott, H. Sakaguchi, L. Cao, K. Chand, Y. Golbuu, T.J. Martin, J. Mayorga, and M.S. Myksvoll, 2020: Ocean data need a sea change to help navigate the warming world. *Nature*, **582** (7811), 181–183. https://doi.org/10.1038/d41586-020-01668-z

197. Chavez, F.P., M. Min, K. Pitz, N. Truelove, J. Baker, D. LaScala-Grunewald, M. Blum, K. Walz, C. Nye, A. Djurhuus, R.J. Miller, K.D. Goodwin, F.E. Muller-Karger, H.A. Ruhl, and C.A. Scholin, 2021: Observing life in the sea using environmental DNA. *Oceanography*, **34** (2), 102–119. https://doi.org/10.5670/oceanog.2021.218

198. Roemmich, D., L. Talley, N. Zilberman, E. Osborne, K. Johnson, L. Barbero, H. Bittig, N. Briggs, A. Fassbender, G. Johnson, B. King, E. McDonagh, S. Purkey, S. Riser, T. Suga, Y. Takeshita, V. Thierry, and S. Wijffels, 2021: The technological, scientific, and sociological revolution of global subsurface ocean observing. *Oceanography*, **34** (4), 2–8. https://doi.org/10.5670/oceanog.2021.supplement.02-02

199. Schmidt, J.O., S.J. Bograd, H. Arrizabalaga, J.L. Azevedo, S.J. Barbeaux, J.A. Barth, T. Boyer, S. Brodie, J.J. Cárdenas, S. Cross, J.-N. Druon, A. Fransson, J. Hartog, E.L. Hazen, A. Hobday, M. Jacox, J. Karstensen, S. Kupschus, J. Lopez, L.A.S.-P. Madureira, J.E. Martinelli Filho, P. Miloslavich, C.P. Santos, K. Scales, S. Speich, M.B. Sullivan, A. Szoboszlai, D. Tommasi, D. Wallace, S. Zador, and P.A. Zawislak, 2019: Future ocean observations to connect climate, fisheries and marine ecosystems. *Frontiers in Marine Science*, **6**, 550. https://doi.org/10.3389/fmars.2019.00550

200. Berkes, F., J. Colding, and C. Folke, 2000: Rediscovery of traditional ecological knowledge as adaptive management. *Ecological Applications*, **10** (5), 1251–1262. https://doi.org/10.2307/2641280

201. Lam, D.P.M., E. Hinz, D.J. Lang, M. Tengö, H. von Wehrden, and B. Martín-López, 2020: Indigenous and local knowledge in sustainability transformations research: A literature review. *Ecology and Society*, **25** (1), 3. https://doi.org/10.5751/es-11305-250103

202. Moltmann, T., J. Turton, H.-M. Zhang, G. Nolan, C. Gouldman, L. Griesbauer, Z. Willis, Á.M. Piniella, S. Barrell, E. Andersson, C. Gallage, E. Charpentier, M. Belbeoch, P. Poli, A. Rea, E.F. Burger, D.M. Legler, R. Lumpkin, C. Meinig, K. O'Brien, K. Saha, A. Sutton, D. Zhang, and Y. Zhang, 2019: A Global Ocean Observing System (GOOS), delivered through enhanced collaboration across regions, communities, and new technologies. *Frontiers in Marine Science*, **6**, 291. https://doi.org/10.3389/fmars.2019.00291

203. Colgan, C.S., P. King, and S. Jenkins, 2021: California Coastal Recreation: Beyond the Beach. Publications. 1. Middlebury Institute of International Studies at Monterey, Center for the Blue Economy. https://cbe.miis.edu/publications/1

204. ERG and Synapse Energy Economics, 2020: Volume 2. Cost of doing nothing analysis. In: *Assessing the Impacts Climate Change May Have on the State's Economy, Revenues, and Investment Decisions: Summary Report*. Eastern Research Group and Synapse Energy Economics, Augusta, ME, 9–13. https://www.maine.gov/future/sites/maine.gov.future/files/inline-files/ERG_MCC_AssessingImpactsClimateChangeMaine_Summary.pdf

205. Wall, T.U., E. McNie, and G.M. Garfin, 2017: Use-inspired science: Making science usable by and useful to decision makers. *Frontiers in Ecology and the Environment*, **15** (10), 551–559. https://doi.org/10.1002/fee.1735

206. Jacox, M.G., M.A. Alexander, D. Amaya, E. Becker, S.J. Bograd, S. Brodie, E.L. Hazen, M. Pozo Buil, and D. Tommasi, 2022: Global seasonal forecasts of marine heatwaves. *Nature*, **604** (7906), 486–490. https://doi.org/10.1038/s41586-022-04573-9

207. Jacox, M.G., M.A. Alexander, S. Siedlecki, K. Chen, Y.-O. Kwon, S. Brodie, I. Ortiz, D. Tommasi, M.J. Widlansky, D. Barrie, A. Capotondi, W. Cheng, E. Di Lorenzo, C. Edwards, J. Fiechter, P. Fratantoni, E.L. Hazen, A.J. Hermann, A. Kumar, A.J. Miller, D. Pirhalla, M. Pozo Buil, S. Ray, S.C. Sheridan, A. Subramanian, P. Thompson, L. Thorne, H. Annamalai, K. Aydin, S.J. Bograd, R.B. Griffis, K. Kearney, H. Kim, A. Mariotti, M. Merrifield, and R. Rykaczewski, 2020: Seasonal-to-interannual prediction of North American coastal marine ecosystems: Forecast methods, mechanisms of predictability, and priority developments. *Progress in Oceanography*, **183**, 102307. https://doi.org/10.1016/j.pocean.2020.102307

208. Liu, G., C.M. Eakin, M. Chen, A. Kumar, J.L. De La Cour, S.F. Heron, E.F. Geiger, W.J. Skirving, K.V. Tirak, and A.E. Strong, 2018: Predicting heat stress to inform reef management: NOAA Coral Reef Watch's 4-month coral bleaching outlook. *Frontiers in Marine Science*, **5**, 57. https://doi.org/10.3389/fmars.2018.00057

209. Mills, K.E., A.J. Pershing, and C.M. Hernández, 2017: Forecasting the seasonal timing of Maine's lobster fishery. *Frontiers in Marine Science*, **4**, 337. https://doi.org/10.3389/fmars.2017.00337

210. Tommasi, D., C.A. Stock, A.J. Hobday, R. Methot, I.C. Kaplan, J.P. Eveson, K. Holsman, T.J. Miller, S. Gaichas, M. Gehlen, A. Pershing, G.A. Vecchi, R. Msadek, T. Delworth, C.M. Eakin, M.A. Haltuch, R. Séférian, C.M. Spillman, J.R. Hartog, S. Siedlecki, J.F. Samhouri, B. Muhling, R.G. Asch, M.L. Pinsky, V.S. Saba, S.B. Kapnick, C.F. Gaitan, R.R. Rykaczewski, M.A. Alexander, Y. Xue, K.V. Pegion, P. Lynch, M.R. Payne, T. Kristiansen, P. Lehodey, and F.E. Werner, 2017: Managing living marine resources in a dynamic environment: The role of seasonal to decadal climate forecasts. *Progress in Oceanography*, **152**, 15–49. https://doi.org/10.1016/j.pocean.2016.12.011

211. Bell, R., A. Strawn, and G. Kirchner, 2021: Flexibility in the Pacific Fisheries Management Council's Fishery Management Plans: What is Flexible Fisheries Management? The Nature Conservancy, Portland, OR. https://pfmc.psmfc.org/CommentReview/DownloadFile?p=5fdeb210-d94e-44e0-9fc5-a2c79ef1f2c3.pdf&fileName=1.2_Climate%20and%20Communities%20Initiative%20Update_Flexibility%20White%20Paper_TNC.pdf

212. Drenkard, E.J., C. Stock, A.C. Ross, K.W. Dixon, A. Adcroft, M. Alexander, V. Balaji, S.J. Bograd, M. Butenschön, W. Cheng, E. Curchitser, E.D. Lorenzo, R. Dussin, A.C. Haynie, M. Harrison, A. Hermann, A. Hollowed, K. Holsman, J. Holt, M.G. Jacox, C.J. Jang, K.A. Kearney, B.A. Muhling, M.P. Buil, V. Saba, A.B. Sandø, D. Tommasi, and M. Wang, 2021: Next-generation regional ocean projections for living marine resource management in a changing climate. *ICES Journal of Marine Science*, **78** (6), 1969–1987. https://doi.org/10.1093/icesjms/fsab100

213. IPCC, 2022: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp. https://doi.org/10.1017/9781009325844

214. Daniel, R., 2019: Understanding our environment requires an indigenous worldview. *Eos*, **100**. https://doi.org/10.1029/2019eo137482

215. 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: Ch. 9. 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. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 353–390. https://doi.org/10.7930/nca4.2018.ch9

216. Levin, L.A., B.J. Bett, A.R. Gates, P. Heimbach, B.M. Howe, F. Janssen, A. McCurdy, H.A. Ruhl, P. Snelgrove, K.I. Stocks, D. Bailey, S. Baumann-Pickering, C. Beaverson, M.C. Benfield, D.J. Booth, M. Carreiro-Silva, A. Colaço, M.C. Eblé, A.M. Fowler, K.M. Gjerde, D.O.B. Jones, K. Katsumata, D. Kelley, N. Le Bris, A.P. Leonardi, F. Lejzerowicz, P.I. Macreadie, D. McLean, F. Meitz, T. Morato, A. Netburn, J. Pawlowski, C.R. Smith, S. Sun, H. Uchida, M.F. Vardaro, R. Venkatesan, and R.A. Weller, 2019: Global Observing needs in the deep ocean. *Frontiers in Marine Science*, **6**, 241. https://doi.org/10.3389/fmars.2019.00241

217. Sumaila, U.R., J. Palacios-Abrantes, and W.W.L. Cheung, 2020: Climate change, shifting threat points, and the management of transboundary fish stocks. *Ecology and Society*, **25** (4), 40. https://doi.org/10.5751/es-11660-250440

218. Colgan, C.S., 2016: The economics of adaptation to climate change in coasts and oceans: Literature review, policy implications and research agenda. *Journal of Ocean and Coastal Economics*, **3** (2), 1. https://doi.org/10.15351/2373-8456.1067

219. Constable, A.J., S. Harper, J. Dawson, K. Holsman, T. Mustonen, D. Piepenburg, and B. Rost, 2022: Cross-Chapter paper 6: Polar regions. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2319–2368. https://doi.org/10.1017/9781009325844.023

220. Mcleod, E., G.L. Chmura, S. Bouillon, R. Salm, M. Björk, C.M. Duarte, C.E. Lovelock, W.H. Schlesinger, and B.R. Silliman, 2011: A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. *Frontiers in Ecology and the Environment*, **9** (10), 552–560. https://doi.org/10.1890/110004

221. Sasmito, S.D., D. Murdiyarso, D.A. Friess, and S. Kurnianto, 2016: Can mangroves keep pace with contemporary sea level rise? A global data review. *Wetlands Ecology and Management*, **24** (2), 263–278. https://doi.org/10.1007/s11273-015-9466-7

222. Scarano, F.R., 2017: Ecosystem-based adaptation to climate change: Concept, scalability and a role for conservation science. *Perspectives in Ecology and Conservation*, **15** (2), 65–73. https://doi.org/10.1016/j.pecon.2017.05.003