Congressional Research Service
Informing the legislative debate since 1914

Ocean Acidification: Frequently Asked Questions

November 3, 2022

Congressional Research Service
https://crsreports.congress.gov
R47300

CRS REPORT
Prepared for Members and
Committees of Congress

Ocean Acidification: Frequently Asked Questions

SUMMARY

R47300

November 3, 2022

Caitlin Keating-Bitonti
Analyst in Natural Resources Policy

Eva Lipiec
Analyst in Natural Resources Policy

The ocean absorbs carbon dioxide (CO_2) from the atmosphere. Chemical reactions between CO_2 and water can change the pH of seawater (pH is a measure of water's acidity or basicity). The current shift in the chemistry of seawater is toward a lower pH, commonly referred to as *ocean acidification* (OA). Scientific consensus is that rising CO_2 concentrations in the atmosphere will continue to contribute to OA globally, primarily affecting the ocean's surface waters.

Some U.S. regions are experiencing impacts from OA (e.g., coastal waters of Oregon), and scientists expect that nearly all U.S. coastlines and open ocean waters will experience impacts of OA by 2100. OA also has negatively affected some marine organisms, such as reef-building corals and shellfish, and may affect others in the future. These impacts have had consequences for U.S. fisheries and aquaculture. Future OA's economic impacts may include higher risks of storm damage to coastal communities and loss of tourism revenue from OA-caused degradation of coral reefs.

Congress has authorized federal agencies, such as the National Oceanic and Atmospheric Administration (NOAA) and the Environmental Protection Agency, to support activities that aim to adapt to and mitigate OA impacts. In 2009, Congress passed the Federal Ocean Acidification Research and Monitoring Act (FOARAM; 33 U.S.C. §§3701 et seq.), which, among other things, established the federal Interagency Working Group on Ocean Acidification (IWGOA) to coordinate OA activities across the federal government. IWGOA's work includes studying OA's potential impact on marine species and ecosystems as well as identifying adaptation and mitigation strategies.

Congress continues to show interest in OA. In 2022, Congress enacted the Coastal and Ocean Acidification Research and Innovation Act of 2021 (P.L. 117-167, Title VI, Subtitle E), which amended FOARAM. The amendments added acidification of coastal waters as a concern to be addressed; established an advisory board to the IWGOA; emphasized research on OA adaptation and mitigation strategies, the compounding effects of OA with other environmental stressors, and the socioeconomic impacts of OA; and authorized appropriations for NOAA and the National Science Foundation to conduct OA activities.

Also in 2022, Congress provided funding to NOAA for OA activities in the Consolidated Appropriations Act, 2022 (P.L. 117-103). During the 117th Congress, Members have introduced and considered other bills related to OA, some of which focused on examining and addressing the impacts of OA, among other activities. Proposed FY2023 appropriations bills would provide NOAA with increased funding compared with FY2022 levels and additional OA-related directives.

Contents

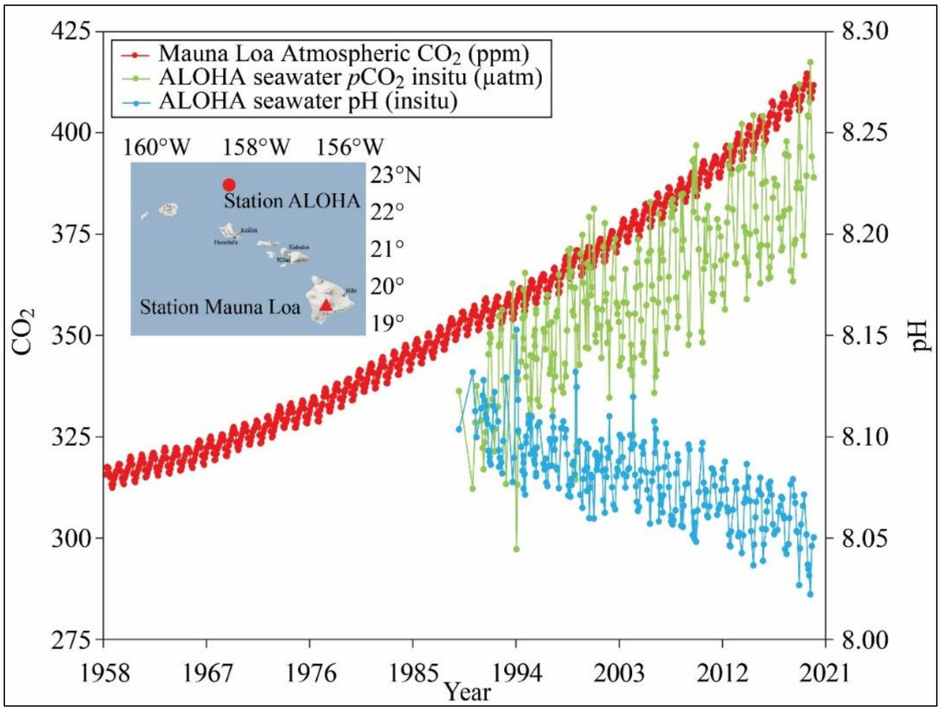
Figures

Contacts

What Is Ocean Acidification?

Atmospheric gases, such as carbon dioxide (CO_2), continuously diffuse into the surface of the ocean.[1] Dissolved gases in the surface of the ocean are in near equilibrium with gases in the atmosphere. Thus, as more CO_2 is emitted into the atmosphere, the surface of the ocean takes up more CO_2. The increased uptake of atmospheric CO_2 by the ocean alters the chemistry of seawater by decreasing its pH in a process referred to as *ocean acidification*, or OA (**Figure 1**).[2]

Figure 1. Pacific Atmospheric and Seawater Carbon Dioxide Concentrations and Seawater pH



Source: National Oceanic and Atmospheric Administration (NOAA), "Hawaii Carbon Dioxide Time-Series," at https://www.pmel.noaa.gov/co2/file/Hawaii+Carbon+Dioxide+Time-Series.

Notes: Figure shows the relationship between atmospheric carbon dioxide (CO_2) concentrations (red points and line) and dissolved CO_2 concentrations of seawater in surface ocean (green points and line), as well as the relationship between increasing dissolved CO_2 concentrations in surface ocean (green points and line) and decreasing seawater pH (blue points and line). Atmospheric CO_2 measurements were made at Mauna Loa Baseline Observatory (refer to Station Mauna Loa on the insert map), which has been continuously monitoring and collecting data related to atmospheric change since the 1950s (NOAA, "Mauna Loa Baseline Observatory," at https://gml.noaa.gov/obop/mlo/). Dissolved CO_2 and pH measurements were made at Station ALOHA, a circle

[1] The surface mixed layer depth of the ocean varies seasonally and geographically but generally is between 0 and 200 meters beneath the surface of the ocean.

[2] Rising carbon dioxide (CO_2) emissions are the root cause for current surface ocean acidification (OA). In the ocean interior, bacteria break down organic matter during *cellular respiration,* which adds CO_2 to seawater (see "What Factors Influence Ocean Acidification?"). Woods Hole Oceanographic Institution, "Ocean Acidification," at https://www.whoi.edu/know-your-ocean/ocean-topics/how-the-ocean-works/ocean-chemistry/ocean-acidification/; and National Oceanic and Atmospheric Administration (NOAA), "Ocean Acidification," at https://www.noaa.gov/education/resource-collections/ocean-coasts/ocean-acidification.

of a 6-mile radius in the Pacific Ocean north of Hawaii (refer to Station ALOHA on the insert map), which has been collecting oceanographic data since 1988 (Station ALOHA, at https://aco-ssds.soest.hawaii.edu/ALOHA/).

OA alters seawater chemistry following a series of chemical reactions. When atmospheric CO_2 dissolves into water (H_2O), it forms carbonic acid (H_2CO_3). Some of the carbonic acid breaks up in ocean water, producing free hydrogen ions (H^+). As the number of free hydrogen ions increases, the pH of the ocean decreases and the water becomes more acidic. The prevailing global average pH (a measure of hydrogen ion concentration) of water near the ocean surface is around 8.1, with regional variations.[3]

How Might Ocean Acidification Change over the 21st Century?

Over the past two centuries, the average pH of water near the ocean surface has decreased by almost 0.1 unit.[4] That change represents a 26% increase in the concentration of free hydrogen ions dissolved in seawater, because the pH scale is logarithmic (i.e., water with a pH of 8.0 is 10 times less acidic than water with a pH of 7.0 and 100 times less acidic than water with a pH of 6.0).

Modeling studies project that OA will continue over the 21st century, but the rate of OA likely will depend on the rate of atmospheric CO_2 emissions.[5] Under the Intergovernmental Panel on Climate Change's scenario involving a doubling of the concentration of atmospheric CO_2 by 2050 with no additional climate change policies, models project that average surface ocean pH may decrease by 0.4 units by the year 2100 (**Figure 2**).[6] However, using a scenario in which CO_2 emissions reach net zero by 2050 or shortly thereafter, models project that average surface ocean pH may decrease by less than 0.1 unit by 2050 and may rise slightly in the second half of the 21st century (**Figure 2**).[7] **Figure 2** also shows the projected pathway of ocean surface pH for other CO_2 emissions scenarios in modeling studies.[8]

[3] The pH scale is an inverse logarithmic representation of hydrogen ion (H+) concentration, indicating the activity of hydrogen ions (or their equivalent) in the solution. A pH of less than 7.0 is considered *acidic*, a pH greater than 7.0 is considered *basic*, and a pH level of 7.0 is defined as *neutral*.

[4] James Orr et al., "Anthropogenic Ocean Acidification over the Twenty-First Century and Its Impact on Calcifying Organisms," *Nature*, vol. 437 (2005); and NOAA, "Ocean Acidification," at https://www.noaa.gov/education/resource-collections/ocean-coasts/ocean-acidification.

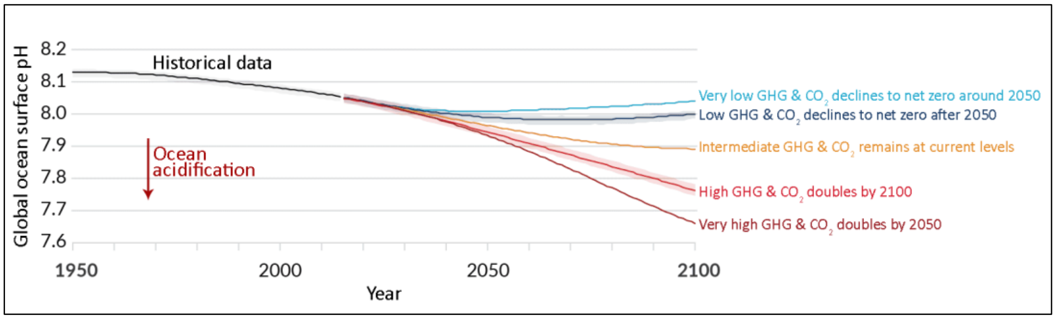
[5] IPCC, *AR6 Physical Science Basis*, Chapter 5, p. 720.

[6] Ibid., p. 714.

[7] *Net-zero emissions* means that some greenhouse gases (GHGs) are emitted, but these emissions are offset by removing an equivalent amount of GHGs from the atmosphere and storing it permanently in soil, plants, or materials. Achieving *net-zero emissions* may be considered more feasible than releasing no GHGs to the atmosphere (i.e., *zero emissions*).

[8] IPCC, *AR6 Physical Science Basis*, Chapter 5, p. 720.

Figure 2. Scenario Projections of Global Ocean Surface pH



Source: CRS with information from Intergovernmental Panel on Climate Change, "Summary for Policymakers," in *Changing Climate 2021: The Physical Science Basis*, eds. Valerie Masson-Delmotte et al., 2021, p. SMP-22.

Notes: CO_2 = carbon dioxide; GHG = greenhouse gas. Models project decreasing ocean surface pH through the 21st century for scenarios with intermediate to very high GHG emissions (yellow, red, and maroon lines) and decreasing pH until around 2070, but that rises slightly after 2070 for scenarios with very low to low GHG emissions (light and dark blue lines). The light blue line holds global warming to about 1.5 degrees Celsius (°C), in line with the goals of the Paris Agreement; the dark blue line holds global warming to beneath 2°C.

Model projections of average global OA changes, such as the projections shown in **Figure 2**, are driven primarily by atmospheric CO_2 simulations.[9] In general, the global trend would reflect surface pH decline with increasing atmospheric CO_2 concentrations. Regional seawater properties may influence the surface pH value, resulting in geographic variations in OA.[10] See "What Factors Influence Ocean Acidification?" for a further discussion on the factors that may amplify regional variations in seawater pH.

What Factors Influence Ocean Acidification?

Not all ocean and coastal regions experience OA in the same way. Increased CO_2 concentrations in the atmosphere contribute to OA, but other factors also influence coastal and ocean acidification. Rates of acidification can vary geographically for numerous reasons, including temperature, ocean circulation, biological activity, coastal upwelling, freshwater input, and nutrient runoff, among other influences.[11]

- **Temperature**. Gases, such as CO_2, are more soluble in colder water than in warmer water. Thus, marine waters near the poles have a much greater capacity to absorb atmospheric CO_2 than do ocean waters in the tropics. As a consequence, polar regions tend to experience greater regional changes due to OA.[12]
- **Ocean Circulation**. Dissolved CO_2 is transported from the ocean surface into deeper ocean water at high latitudes, because cold polar surface waters have a higher density than warm tropical waters. The cold polar surface waters sink to depth (i.e., vertical ocean mixing), and both observations and modeling studies

[9] IPCC, *AR6 Physical Science Basis*, Chapter 5, p. 719.

[10] Ibid.

[11] Josep G. Canadell et al., "Chapter 5: Global Carbon and Other Biogeochemical Cycles and Feedbacks," in *Changing Climate 2021: The Physical Science Basis*, Intergovernmental Panel on Climate Change (IPCC), eds. Valerie Masson-Delmotte et al., 2021, p. 720 (hereinafter referred to as IPCC, *AR6 Physical Science Basis*).

[12] IPCC, *AR6 Physical Science Basis*, Chapter 5, p. 677.

show that the vertical ocean mixing contributes to acidification of the deeper ocean.[13] For example, OA below 2,000 meters has been detected in polar regions in both the North Atlantic and the Southern Ocean.[14]

- **Biological Activity**. The breakdown of organic carbon in the ocean interior by bacteria, via a biological process known as *cellular respiration*, adds CO_2 to seawater. Deep ocean water is enriched in CO_2 due to cellular respiration, in addition to the capacity of colder water in the deep ocean to absorb CO_2. Phytoplankton near the ocean surface and marine plants (i.e., kelp, seaweed, seagrass) take up CO_2 during *photosynthesis*, which may offset some effects of OA.
- **Coastal Upwelling**. *Coastal upwelling* is a process by which coastal winds push warm surface waters offshore, causing cold deep water to rise to the surface. Upwelled ocean waters have high CO_2 concentrations, because deep ocean waters carry dissolved CO_2 from two sources: (1) atmospheric CO_2 from when cold polar waters were last at the surface of the ocean and (2) CO_2 respired by bacteria during the decomposition of organic carbon in the ocean interior.[15]
- **Freshwater Input**. Riverine influx associated with high-intensity precipitation events or glacial melt can yield large freshwater inputs that contribute dissolved inorganic carbon, organic carbon, and nutrients to coastal waters. These contributions can alter the chemistry of waters located at the mouths of large rivers or the toes of glaciers. In addition, rainwater is naturally acidic, due to CO_2 and other atmospheric gases, such as nitrogen dioxide.[16]
- **Nutrient Runoff**. Riverine inputs with high nutrient loads (often nitrogen and phosphorous associated with farming practices) can lead to excessive plant and algae growth in coastal settings, a process known as *eutrophication*.[17] The resulting decomposition of algae and plants in coastal waters produces increased amounts of CO_2 in the water column, which can lead to a lowering of seawater pH.[18]

How Does Ocean Acidification Impact Marine Life?

The influence of OA on marine life is complicated. A pH of less than the global average of 8.1 may cause some organisms to expend more energy, but organisms may be able to adapt in complex and species-specific ways to OA. OA may affect more marine species when compounded by the effects of climate change, including warming seawater temperatures and deoxygenation (loss of oxygen).[19] In particular, OA poses physiological stress to invertebrate

[13] IPCC, *AR6 Physical Science Basis*, Chapter 5, p. 717.

[14] Ibid.

[15] U.S. Global Change Research Program (USGCRP), "Chapter 13: Ocean Acidification and Other Ocean Changes," in *Climate Science Special Report: Fourth National Climate Assessment*, vol. I, eds. Donald J. Wuebbles et al., 2017, p. 373 (hereinafter referred to as USGCRP, NCA4 vol. I). For a discussion on coastal upwelling, see CRS Report R47021, *Federal Involvement in Ocean-Based Research and Development*, by Caitlin Keating-Bitonti.

[16] Rainwater is naturally acidic at a pH of around 5.6.

[17] U.S. Environmental Protection Agency (EPA), "The Sources and Solutions: Agriculture," at https://www.epa.gov/nutrientpollution/sources-and-solutions-agriculture.

[18] NOAA, "What Is Eutrophication?," at https://oceanservice.noaa.gov/facts/eutrophication.html.

[19] IPCC, *AR6 Physical Science Basis*, p. 721.

organisms that build their hard parts (i.e., shells, skeletons, reef structures) with carbonate minerals.[20]

Marine Invertebrates

For many marine invertebrate organisms, the abundance and availability of carbonate ions (CO_3^{2-}) in seawater are critical for survival. Most marine invertebrates have biochemical mechanisms to regulate internal pH and are able, within limits, to grow their hard parts even when water external to their internal environment is acidic. At current average ocean pH levels (about 8.1), ocean waters near the surface have ample carbonate ions to support shell formation and coral reef growth. However, as more CO_2 dissolves into the ocean, the abundance and availability of carbonate ions decline due to chemical reactions.[21] A reduction in the availability of carbonate ions in the ocean makes it physiologically challenging for shell-forming marine organisms to grow shells, especially those in early stages of their life cycle (i.e., larval and juvenile stages). If the availability of carbonate ions becomes too low (i.e., undersaturated) in seawater, then shells made with carbonate minerals tend to dissolve.

The following sections expound on current or potential impacts of OA on invertebrate species, including corals, oysters, lobsters, and crabs.

Corals

OA reduces corals' ability to build and maintain reefs, the majority of which are located in tropical and subtropical shallow waters. Most corals are colonial organisms, comprising hundreds to hundreds of thousands of individual animals, called *polyps*.[22] Some polyps secrete carbonate skeletons that can grow into very large reef structures, called *coral reefs*. Modeling studies employing an emissions scenario in which very little climate change mitigation is undertaken this century project 2100 seawater pH conditions that are less favorable to the growth of coral reefs (refer to the maroon line in **Figure 2**).[23]

Coral reefs are biodiverse, productive ecosystems that can provide socioeconomic benefits to coastal communities. For example, studies show that reefs provide protection against waves comparable to that provided by artificial structures such as *breakwaters*.[24] Coral reef recreation and tourism generate an estimated $192 million per year for Puerto Rico and $96 million per year for the U.S. Virgin Islands.[25] Coral reefs contribute an estimated $477 million to Hawaii's economy every year.[26] In addition to potential impacts on tourism, declines in coral reef cover

[20] Carbonate minerals include aragonite, calcite, and high-magnesium calcite.

[21] As more CO_2 dissolves into the ocean, bicarbonate ions (HCO_3^{1-}) form at the expense of carbonate ions (CO_3^{2-}), which is described by the following reaction: $CO_2 + CO_3^{2-} + H_2O = 2HCO_3^{1-}$.

[22] NOAA, "What Are Corals?," at https://oceanservice.noaa.gov/education/tutorial_corals/coral01_intro.html.

[23] USGCRP, "Chapter 27: Hawai'i and U.S.-Affiliated Pacific Islands," in *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment*, vol. II, eds. David R. Reidmiller et al., 2018, p. 1264 (hereinafter referred to as USGCRP, NCA4 vol. II); and K.L. Ricke et al., "Risks to Coral Reefs from Ocean Carbonate Chemistry Changes in Recent Earth System Model Projections," Environmental Research Letters, vol. 8 (2013), p. 5.

[24] Filippo Ferrario et al., "The Effectiveness of Coral Reefs for Coastal Hazard Risk Reduction and Adaptation," *Nature Communications*, vol. 5 (2014); and U.S. National Park Service, "Breakwaters, Headlands, Sills, and Reefs," at https://www.nps.gov/articles/breakwaters-headlands-sills-and-reefs.htm.

[25] USGCRP, NCA4 vol. II, Chapter 20, p. 829.

[26] USGCRP, NCA4 vol. II, Chapter 27, p. 1245.

may reduce fisheries' maximum catch potential in the exclusive economic zones of most central and western Pacific islands and in the Caribbean region.[27]

Shellfish

OA's effects on certain shellfish has impacted shellfish fishery revenues and may continue to do so should OA expand to new regions and greater water depths.[28] Of particular relevance to shellfish hatcheries, relatively acidic ocean conditions caused by OA may impair the ability of larval shellfish to build shells. For example, in the mid-2000s, oyster growers from Washington to California experienced financial hardships from widespread death of larval shellfish (seed) at hatcheries.[29] In 2008, scientists from the National Oceanic and Atmospheric Administration (NOAA) and various universities linked the oyster seed losses to OA; in turn, oyster hatcheries shifted their operations to adapt to the OA conditions (see "What Is the Federal Government Doing About Ocean Acidification?").[30] An additional consideration regarding OA's impact on oysters is the potential reduction in shell thickness and hardness, which could devalue oysters commercially because a sought-after characteristic of oysters on the half shell is a shell that is easily shucked and does not break or chip.[31]

OA also may affect other economically valuable shellfish, including the American lobster and Dungeness crab. In 2019, the most recent year reported by NOAA Fisheries, the American lobster found along the coast of New England was the highest-valued shellfish species in North America.[32] The Gulf of Maine, an area with record high stock abundance of American lobster,[33] has experienced changing oceanographic conditions.[34] Ocean warming has influenced lobster fisheries in the region,[35] and some research studies project the Gulf of Maine will experience OA conditions by 2050.[36] In the laboratory, researchers have shown that OA impacts both juvenile and adult lobsters by causing erratic heart rates and fewer infection-fighting blood cells; should these laboratory conditions occur in nature, they may impact lobsters' survival.[37] On the U.S.

[27] USGCRP, NCA4 vol. II, Chapter 27, p. 1264; and USGCRP, NCA4 vol. II, Chapter 20, p. 853.

[28] Sarah Cooley and Scott Doney, "Anticipating Ocean Acidification's Economic Consequences for Commercial Fisheries," *Environmental Research Letters*, vol. 4 (2009).

[29] Ryan Kelly, "Narratives Can Motivate Environmental Action: The Whiskey Creek Ocean Acidification Story," *Ambio*, vol. 43 (2014), pp. 592-599.

[30] Ibid. and NOAA, "Improving an Ocean Acidification Observation System in Support of Pacific Coast Shellfish Growers," at https://ioos.noaa.gov/project/turning-headlights-high/.

[31] Catherine Liberti et al., "The Impact of Oyster Aquaculture on the Estuarine Carbonate System," *Elementa: Science of the Anthropocene*, vol. 10 (2022).

[32] NOAA Fisheries reported a total commercial catch of 132.6 million pounds of American lobster, yielding nearly $910 million dollars, in 2021 (NOAA Fisheries, "Landings," at https://www.fisheries.noaa.gov/foss/f?p=215:200:14333709901427:Mail:NO, hereinafter referred to as NOAA Fisheries, Landings Database). NOAA Fisheries, "U.S. Fisheries by the Numbers," at https://www.fishwatch.gov/sustainable-seafood/by-the-numbers.

[33] NOAA, "American Lobster," at https://www.fisheries.noaa.gov/species/american-lobster.

[34] Samantha Siedlecki et al., "Projecting Ocean Acidification Impacts for the Gulf of Maine into 2050: New Tools and Expectations," *Elementa: Science of the Anthropocene*, vol. 9 (2021).

[35] Katherine Mills et al., "Fisheries Management in a Changing Climate: Lessons from the 2012 Ocean Heat Wave in the Northwest Atlantic," *Oceanography*, vol. 26 (2013), pp. 191-195.

[36] Samantha Siedlecki et al., "Projecting Ocean Acidification Impacts for the Gulf of Maine into 2050: New Tools and Expectations," *Elementa: Science of the Anthropocene*, vol. 9 (2021).

[37] Amalia Harrington and Heather Hamlin, "Ocean Acidification Alters Thermal Cardiac Performance, Hemocyte Abundance, and Hemolymph Chemistry in Subadult American Lobsters *Homarus americanus* H. Milne Edwards, 1837 (Decapoda: Malcostraca: Nephropidae)," *Journal of Crustacean Biology*, vol. 39, no. 4 (2019), pp. 468-476.

West Coast, Dungeness crabs are a valuable shellfish.[38] Dungeness crabs have shown no change in natural population dynamics due to changing oceanographic conditions. Laboratory experiments have found decreased survival rates in Dungeness crabs hatched in waters with a pH of 7.5 (a level that has been observed in upwelled waters along the Washington coast) compared with those hatched in laboratory waters with a global average pH of 8.1.[39]

Marine Vertebrates

Whereas invertebrate organisms primarily build their hard parts with carbonate minerals, vertebrate bones, including those of fish, are composed of a phosphate mineral. OA does not affect the chemical structure of phosphate. Some studies, however, show that the durability and robustness of some fish bones and shark teeth increase under OA conditions.[40] Other studies have claimed that OA can alter the behaviors of certain fish species, but the research methodology behind these studies is debated.[41]

How Might U.S. Regions Be Affected by Ocean Acidification?

Some U.S. regions have experienced measurable impacts from OA. Scientists expect that nearly all U.S. coastlines will experience the impacts of OA by 2100.[42] As shown in **Figure 2**, models project a decrease in global ocean surface pH ranging from about 0.05 to 0.10 units by 2050. As discussed above, regional seawater properties may affect the surface pH value, resulting in geographic variations of OA.

Pacific waters along the West Coast of the United States are influenced by coastal upwelling. Observations and models project the California Current System may experience an expansion and intensification of low-pH water due to upwelling.[43] OA has impacted some oyster hatcheries along the West Coast. In particular, in 2007, the Oregon-based Whiskey Creek Shellfish Hatchery was unable to provide shellfish growers with late-stage oyster larvae because the low-pH seawater corroded the shells of early stage larvae.[44] Waters circulating around Alaska's Pacific

[38] NOAA Fisheries reported a total commercial catch of 64.2 million pounds of Dungeness crab in 2021, yielding a total revenue of $311.9 million for the Pacific Coast. Of this total, the total catch for Alaska was 9.0 million pounds, with a revenue of $37.8 million. NOAA Fisheries, Landings Database.

[39] Nina Bednarŝek et al., "Exoskeleton Dissolution with Mechanoreceptor Damage in Larval Dungeness Crab Related to Severity of Present-Day Ocean Acidification Vertical Gradients," *Science of the Total Environment*, vol. 716 (2020); and NOAA, "Dungeness Crab Larvae Already Showing Effects of Coastal Acidification," January 23, 2020, at https://research.noaa.gov/article/ArtMID/587/ArticleID/2581.

[40] Jonathan Leung et al., "Shark Teeth Can Resist Ocean Acidification," *Global Change Biology*, vol. 28, no. 7 (2022); Valentina Di Santo, "Ocean Acidification and Warming Affect Skeletal Mineralization in a Marine Fish," *Proceedings of the Royal Society B: Biological Sciences*, vol. 268 (2019); and Alice Mirasole et al., "Evidences On Alterations in Skeleton Composition and Mineralization in a Site-Attached Fish Under Naturally Acidified Conditions in a Shallow CO_2 Vent," *Science of the Total Environment*, vol. 761 (2021).

[41] See Martin Enserink, "Sea of Doubts," *Science* (2021), at https://www.science.org/content/article/does-ocean-acidification-alter-fish-behavior-fraud-allegations-create-sea-doubt.

[42] USGCRP, NCA4 vol. I; and USGCRP, NCA4 vol. II.

[43] See the previous question for more information about coastal upwelling. IPCC, *AR6 Physical Science Basis*, Chapter 5, p. 721.

[44] NOAA, "Improving an Ocean Acidification Observation System in Support of Pacific Coast Shellfish Growers," at https://ioos.noaa.gov/project/turning-headlights-high/; and R. Kelly, "Narratives Can Motivate Environmental Action:

coastline also are derived from upwelled cold waters and may be impacted by OA.[45] Moreover, glacial runoff may further amplify OA along the Alaskan coast (e.g., Gulf of Alaska).[46]

U.S. coastal regions near agricultural watersheds and urbanized estuaries may be susceptible to OA due to eutrophication.[47] For example, the Mississippi River delivers riverine inputs of nutrients (nitrogen and phosphorus) to the Gulf of Mexico, contributing to eutrophication of coastal waters and a decrease in pH.[48] Similarly, runoff into the Chesapeake Bay is contributing to eutrophication and a decrease in pH in the Bay's waters.[49] In addition, coastal waters of the East Coast and the mid-Atlantic are influenced by freshwater inputs from riverine and estuarine sources, which may contribute to OA.[50]

Tropical oceans are expected to experience the greatest change in seawater chemistry associated with rising atmospheric CO_2 concentrations.[51] The seawater pH off the Hawaiian Island of Oahu has declined from an annual average of about 8.11 to 8.07 (roughly an 8.7% increase in acidity), according to 34 years of ocean data collection at Station ALOHA (**Figure 1**).[52] Although oceanic pH varies geographically, scientists consider the conditions at Station ALOHA to be broadly representative of those across the western and central Pacific Ocean.[53] The tropical and subtropical Pacific Ocean also is projected to experience the highest levels of thermal stress, which could exacerbate the effects of increasing OA.[54]

Has Ocean Acidification Happened in the Past?

OA has occurred in the past when geologic events (e.g., volcanic eruptions) emitted large quantities of CO_2 and other gases to the atmosphere. The fossil record suggests that some mass extinction events of marine organisms that have occurred in geologic history may have been related to changes in ocean pH. For example, approximately 56 million years ago, a large pulse of methane locked in ocean sediments was released into the ocean-atmosphere system over a 3,000-20,000 year period.[55] Methane released into the ocean-atmosphere undergoes a chemical reaction to become CO_2 within about 10 years. Chemical analyses of marine sediments suggest this

The Whiskey Creek Ocean Acidification Story," *Ambio*, vol. 43 (2014).

45 Jeremy Mathis, "Ocean Acidification Risk Assessment for Alaska's Fishery Sector," *Progress in Oceanography*, vol. 136 (2015).

46 Ibid; IPCC, *AR6 Physical Science Basis*, Chapter 5, p. 720.

47 NOAA, "What Is Eutrophication?," at https://oceanservice.noaa.gov/facts/eutrophication.html.

48 IPCC, *AR6 Physical Science Basis*, Chapter 5, p. 721.

49 NOAA, "OPA Projects in the Southeast U.S.," at https://oceanacidification.noaa.gov/CurrentProjects/Southeast.aspx#.

50 USGCRP, NCA4 vol. I, Chapter 13, p. 373.

51 OA generally occurs in shallow ocean waters in tropical regions because there is little to no vertical ocean mixing to transport the atmospheric CO_2 absorbed by the surface ocean into the deep ocean.

52 Data collection and observations began at the Station ALOHA in October 1988.

53 John Marra and Michael Kruk, "State of Environmental Conditions in Hawaii and the U.S. Affiliated Pacific Islands und a Changing Climate: 2017," NOAA National Centers for Environmental Information, 2017, p. 74, at https://coralreefwatch.noaa.gov/satellite/publications/state_of_the_environment_2017_hawaii-usapi_noaa-nesdis-ncei_oct2017.pdf

54 Ibid.

55 Miriam Katz et al., "Uncorking the Bottle: What Triggered the Paleocene/Eocene Thermal Maximum Methane Release?," *Paleoceanography*, vol. 16 (2001); James Zachos et al., "Rapid Acidification of the Ocean During the Paleocene-Eocene Thermal Maximum," *Science*, vol. 308 (2005); and IPCC, *AR6 Physical Science Basis*, Chapter 5, p. 714.

methane release was associated with a global surface ocean pH decline ranging from 0.15 to 0.30 units. However, this change in pH occurred more slowly than the current rate of OA and continued over a long time interval.[56]

What Actions or Interventions Might Limit or Reduce Ocean Acidification?

Some stakeholders may be interested in limiting or reducing OA and its impacts. Mitigating OA involves decreasing the availability of CO_2 in the ocean by removing it from either the atmosphere or the ocean. The ocean's rate of uptake of atmospheric CO_2 would start to decrease if the concentration of atmospheric CO_2 decreased.

Some shellfish industries have implemented approaches to mitigate CO_2 concentrations in the water. Some shellfish farmers on the Pacific and Atlantic coasts of the United States grow marine plants (e.g., kelp, seaweed, seagrass) as a nature-based approach to offset the effects of OA.[57] Researchers also are exploring an approach that involves placing bags of oyster shells near oyster farms to improve the health of the living oysters.[58] These researchers are testing the hypothesis that, over time, the shells in the bags will dissolve and provide a natural buffer to OA. The placement of oyster shells, or pulverized silicate or carbonate rocks, in seawater can alter the water chemistry by fixing the CO_2 dissolved in the seawater to the added material (i.e., shell, pulverized rock or mineral). This approach for removing dissolved CO_2 from the water is known as *ocean alkalinity enhancement* or *enhanced weathering*.[59]

What Is the Federal Government Doing About Ocean Acidification?

Congress has shown interest in OA and its impacts over the past few decades and has directed federal agencies to take certain actions to address OA. Congress passed the Federal Ocean Acidification Research and Monitoring Act of 2009 (FOARAM; P.L. 111-11) and amended the act in 2022 (amendments described under "What Are Recent Congressional Actions Addressing Ocean Acidification?").[60] As amended, FOARAM

[56] IPCC, *AR6 Physical Science Basis*, Chapter 5, p. 714.

[57] Marine plants remove CO_2 from the surface waters of the ocean via photosynthesis. See, for example, World Wildlife Foundation, "Exploring the Benefits of Kelp Farming in Maine," 2021, at https://www.worldwildlife.org/magazine/issues/winter-2021/articles/exploring-the-benefits-of-kelp-farming-in-maine; and Marketplace, "Could Kelp Help Mitigate Ocean Acidification?," February 22, 2018, at https://www.marketplace.org/2018/02/22/could-kelp-help-oyster-industry-mitigate-effects-ocean-acidification/.

[58] NOAA, "Researchers Explore Using Empty Oyster Shells to Decrease Acidic Seawater," October 13, 2017, at https://seagrant.noaa.gov/News/Article/ArtMID/1660/ArticleID/1661/Researchers-Explore-Using-Empty-Oyster-Shells-to-Decrease-Acidic-Seawater.

[59] National Academies of Sciences, Engineering, and Medicine, *A Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration* (Washington, DC: National Academies Press, 2022), p. 181. For more information on ocean-based CO_2 removal technologies, see CRS Report R47172, *Geoengineering: Ocean Iron Fertilization*, by Caitlin Keating-Bitonti.

[60] 33 U.S.C. §§3701 et seq. See "What Are Recent Congressional Actions Addressing Ocean Acidification" for information on the amendments.

- Established and assigned responsibilities to the federal Interagency Working Group on Ocean Acidification (IWGOA) and a nonfederal advisory board
- Directed the Secretary of Commerce to establish an OA program within NOAA and defined the program's activities[61]
- Instructed the National Science Foundation (NSF) to continue its OA research activities, supporting competitive proposals for OA research, observation, and monitoring
- Charged the National Aeronautics and Space Administration with ensuring space-based monitoring of OA and its impacts
- Authorized appropriations for NOAA and NSF to carry out these activities from FY2023 through FY2027[62]

The IWGOA released a strategic federal research and monitoring plan in 2014.[63] In that plan, the working group listed seven thematic areas of federal research and monitoring activities.[64]

1. Research to understand responses to OA
2. Monitoring of ocean chemistry and biological impacts
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms
4. Technology development and standardization of measurements
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems
6. Education, outreach, and engagement strategy on OA
7. Data management and integration

Federal agencies, such as NOAA and the Environmental Protection Agency, also support activities to adapt to and mitigate OA impacts.[65] For example, following the significant drop in oyster production levels at the Whiskey Creek Shellfish Hatchery in 2007, NOAA deployed a network of sensors off the Northwest Pacific Coast to act as an early warning system for shellfish

[61] Under statute, the federal Interagency Working Group on Ocean Acidification (IWGOA) is chaired by a representative from NOAA and includes representatives from the National Science Foundation; National Atmospheric and Space Administration; Smithsonian Institution; National Institute of Standards and Technology (NIST) of the Department of Commerce; EPA; Bureau of Indian Affairs (BIA), Bureau of Ocean Energy Management, National Park Service, U.S. Fish and Wildlife Service, and U.S. Geological Survey of the Department of the Interior; U.S. Department of Agriculture; Department of State; Department of Energy; Department of the Navy; and other agencies as appropriate.

[62] The Federal Ocean Acidification Research and Monitoring Act of 2009 (FOARAM; P.L. 111-11), as amended, does not provide an authorization of appropriations for the National Aeronautics and Space Administration.

[63] IWGOA was charged with developing a strategic research and monitoring plan to guide federal research on OA and overseeing the plan's implementation (33 U.S.C. §§3703(a)(2)). IWGOA is to submit an updated plan to Congress at least once every five years (33 U.S.C. §§3703(c)(3)). According to NOAA, a revised plan is forthcoming (email correspondence with NOAA Office of Legislative and Intergovernmental Affairs, August 17, 2022).

[64] IWGOA, *Strategic Plan for Federal Research and Monitoring of Ocean Acidification,* March 2014, at https://oceanacidification.noaa.gov/Portals/42/Images/IWGOA Strategic Plan.pdf.

[65] For example, see NOAA Ocean Acidification Program, "Adaptation Strategies," at https://oceanacidification.noaa.gov/WhatWeDo/EducationOutreach/SOARCEWebinars/TabId/3463/PID/16157/evl/0/CategoryID/207/CategoryName/adaptation-strategies/Default.aspx; and EPA, "What EPA Is Doing to Address Ocean and Coastal Acidification," at https://www.epa.gov/ocean-acidification/what-epa-doing-address-ocean-and-coastal-acidification.

hatcheries.[66] The early warning system would alert hatchery managers when upwelling produced relatively colder and lower pH seawater; managers could then time when coastal waters were pumped into the hatchery's oyster larvae tanks to avoid harming the hatcheries. Such early warning systems can help buffer the shellfish industry against OA; larvae grown at the hatchery are sold to commercial shellfish growers. The 2022 FOARAM amendments further emphasized mitigating OA's impacts on marine ecosystems.[67]

The IWGOA's 2016 report on implementation of the strategic plan identified multiple OA-related activities across most of the IWGOA agencies.[68] Of the seven thematic areas outlined in the 2014 strategic plan, most OA activities reported in 2016 were related to (1) research to understand responses to OA and (2) monitoring of ocean chemistry and biological impacts.[69] As of 2016 (the latest update on implementation of the strategic plan), strategic plan actions remaining to be addressed were (7) data management and integration.[70]

The IWGOA's summary report for FY2016 and FY2017 (the most recent available), identified funding levels by agency and research and monitoring activities by geographic area, with a focus on locations of interest to the United States (**Figure 3**).[71] In FY2017, total federal funding for OA activities, including activities with a primary or secondary focus on OA, was approximately $45.7 million. Over the FY2012-FY2017 period, NSF and NOAA reported the highest amount of OA activity funding in FY2017, with totals of $24.3 million and $19.3 million, respectively.[72]

[66] NOAA, "Improving an Ocean Acidification Observation System in Support of Pacific Coast Shellfish Growers," at https://ioos.noaa.gov/project/turning-headlights-high/; and R. Kelly, "Narratives Can Motivate Environmental Action: The Whiskey Creek Ocean Acidification Story," *Ambio*, vol. 43 (2014).

[67] P.L. 117-167, §10642(a)(4).

[68] According to the report, the Smithsonian Institution and the Department of Energy's Pacific Northwest National Laboratory were not members of IWGOA in 2014, so their activities were not included in the 2016 implementation plan. In addition, the U.S. Navy did not contribute to the document because its work on OA is "limited." BIA's activities also were not included in the 2016 implementation plan; NIST's activities were included (National Science and Technology Council [NSTC] Subcommittee on Ocean Science and Technology, *Implementation of the Strategic Plan for Federal Research and Monitoring of Ocean Acidification*, December 2016, p. 33, at https://oceanacidification.noaa.gov/sites/oap-redesign/Documents/IWGOA/OA%20Implementation%20Plan%20FINAL.pdf [hereinafter referred to as NSTC, *Implementation Report*, December 2016]).

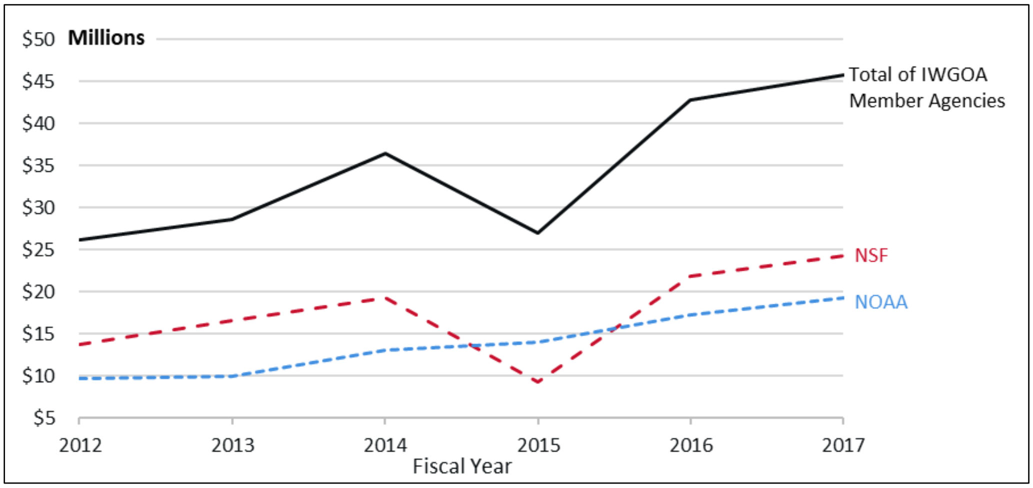
[69] NSTC, *Implementation Report*, December 2016, p. 3.

[70] Ibid.

[71] IWGOA, *Fifth Report on Federally Funded Ocean Acidification Research and Monitoring Activities: Fiscal Years 2016 and 2017*, January 28, 2020, p. 29, at https://oceanacidification.noaa.gov/Portals/42/Federal%20OA%20report%20FY%2016%2017%20%20January%202020.pdf (hereinafter referred to as IWGOA, *Fifth Report*, January 2020). IWGOA is to submit updated reports on implementation and funding to Congress every two years (33 U.S.C. §§3703(c)(2)). According to NOAA, revised reports are forthcoming (email correspondence with NOAA Office of Legislative and Intergovernmental Affairs, August 17, 2022).

[72] IWGOA, *Fifth Report*, January 2020, p. 29.

Figure 3. Trends in Federal Funding of Ocean Acidification Research and Monitoring Activities, FY2012–FY2017



Source: CRS, using Interagency Working Group on Ocean Acidification (IWGOA), *Third Report on Federally Funded Ocean Acidification Research and Monitoring Activities*, April 23, 2015, pp. 20 and 25-26, at https://oceanacidification.noaa.gov/Portals/42/Images/IWGOA%203rd%20Report%20on%20Federal%20Funding%202015%20FINAL%20REVISED.pdf; IWGOA, *Fourth Report on Federally Funded Ocean Acidification Research and Monitoring Activities*, December 20, 2016, pp. 43, 48, and 50, at https://oceanacidification.noaa.gov/sites/oap-redesign/Documents/IWGOA/Fourth%20Report%20on%20OA%20Research%20Monitoring%20FY%2014-15.pdf; and IWGOA, *Fifth Report on Federally Funded Ocean Acidification Research and Monitoring Activities: Fiscal Years 2016 and 2017*, January 28, 2020, p. 29, at https://oceanacidification.noaa.gov/Portals/42/Federal%20OA%20report%20FY%2016%2017%20%20January%202020.pdf.

Notes: Fiscal year total funding for ocean acidification research and monitoring for all IWGOA member agencies (Bureau of Ocean Energy Management, Environmental Protection Agency, Department of State, National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration [NOAA], National Science Foundation [NSF], and U.S. Geological Survey; solid black line) and for the two agencies with the most funding, NSF (dashed red line) and NOAA (dashed blue line). The IWGOA's (fifth) summary report for FY2016 and FY2017 provides the most recent publicly available funding levels and notes that the NSF contributions are underreported. For example, ship support for NSF research activities is provided by NSF-funded University National Oceanographic Laboratory System and is a major expense for OA activities; this expense was not included in data used by CRS to create this figure.

What Are Recent Congressional Actions Addressing Ocean Acidification?

In 2022, Congress enacted the Coastal and Ocean Acidification Research and Innovation Act of 2021 (P.L. 117-167, Title VI, Subtitle E), which amended FOARAM. The amendments included

- The addition of a coastal acidification definition and broadening of agency activities to consider coastal acidification[73]
- The establishment of an advisory board to IWGOA

[73] FOARAM only defined *ocean acidification*. The Coastal and Ocean Acidification Research and Innovation Act of 2021 (P.L. 117-167) amended the ocean acidification definition in FOARAM and defined *coastal acidification* as "the decrease in pH and changes in the water chemistry of coastal oceans, estuaries, and Great Lakes from atmospheric pollutions, freshwater inputs, and excess nutrient run-off from land."

- A greater research focus on OA adaptation and mitigation strategies, on how OA may interact with other environmental stressors, and on the socioeconomic impacts of OA
- Authorization of appropriations for FY2023 through FY2027

In FY2022, Congress appropriated $16 million to NOAA for the Integrated Ocean Acidification Program.[74] Language accompanying the FY2022 appropriations act directed the program to prioritize efforts on "understanding, monitoring, and mitigating coastal ocean acidification, especially where it impacts fisheries and aquaculture"; to provide grants to nonfederal partners to operate "regional-scale research and education centers to address the impacts" of OA; and to establish a prize competition to "stimulate innovation" to advance understanding, research, or monitoring of OA and its impacts or to develop management or adaptation options for responding to OA.[75]

Other bills regarding OA have been introduced in the 117th Congress. Some would direct the Secretary of Commerce or NOAA to work with the National Academies of Sciences, Engineering, and Medicine to examine the impact of OA and other environmental stressors on estuarine environments.[76] Another bill would direct NOAA to support state and local OA vulnerability assessments and strategic research planning related to OA and its impacts on coastal communities, among other OA activities.[77] Some bills would include OA and its impacts as part of broader climate change impacts or physical risks to be addressed in certain ways.[78] In addition, proposed language to accompany House and Senate appropriations acts for FY2023 would increase funding for NOAA's Integrated Ocean Acidification Program.[79] The House committee report would support a prize competition to stimulate OA-related innovation,[80] and the Senate

[74] "Explanatory Statement Submitted by Ms. DeLauro, Chair of the House Committee on Appropriations, Regarding the House Amendment to the Senate Amendment to H.R. 2471, Consolidated Appropriations Act, 2022," *Congressional Record*, vol. 168, No. 42 - Book III (March 9, 2022), p. H1778 (hereinafter referred to as explanatory statement accompanying P.L. 117-103).

[75] U.S. Congress, House Committee on Appropriations, *Commerce, Justice, Science, and Related Agencies Appropriations Bill, 2022,* Report Together with Minority Views to Accompany H.R. 4505, 117th Cong., 1st sess., July 19, 2021, H.Rept. 117-97, p. 43. The explanatory statement accompanying the 2022 Consolidated Appropriations Act states that the "agreement adopts House language regarding the Integrated Ocean Acidification Program" (explanatory statement accompanying P.L. 117-103, p. H1779).

A prize competition to stimulate innovation in understanding and addressing OA was proposed in other legislation, such as H.R. 3764, Section 1011, and H.R. 6061.

[76] For example, H.R. 2533 (passed the House May 18, 2021) and H.R. 3764, Section 1406 (ordered to be reported by the House Committee on Natural Resources).

[77] For example, H.R. 3764, Section 1001 (ordered to be reported by the House Committee on Natural Resources).

[78] For example, H.R. 1187 (passed the House June 16, 2021), H.R. 2570 (reported by the House Committee on Financial Services), H.R. 2780 (ordered to be reported by the House Committee on Natural Resources), H.R. 2872 (ordered to be reported by the House Committee on Natural Resources), and S. 1217 (Senate Committee on Banking, Housing, and Urban Affairs hearings held).

[79] U.S. Congress, House Committee on Appropriations, *Commerce, Justice, Science, and Related Agencies Appropriations Bill, 2023*, Report Together with Minority Views to Accompany H.R. 8256, 117th Cong., 2nd sess., June 30, 2022, H.Rept. 117-395, p. 43 (hereinafter referred to as H.Rept. 117-395); and draft *Explanatory Statement for Commerce, Justice, Science, and Related Agencies Appropriations Bill, 2023*, as posted on the Senate Committee on Appropriations website, July 28, 2022, at https://www.appropriations.senate.gov/news/majority/breaking-chairman-leahy-releases-fiscal-year-2023-senate-appropriations-bills (hereinafter referred to as draft *Senate Explanatory Statement*, 2023).

[80] H.Rept. 117-395.

draft explanatory statement would direct NOAA to work with nonfederal entities on research to complete FOARAM-mandated federal vulnerability assessments.[81]

Author Information

Caitlin Keating-Bitonti
Analyst in Natural Resources Policy

Eva Lipiec
Analyst in Natural Resources Policy

Disclaimer

[81] Draft *Senate Explanatory Statement*, 2023.