United States Government Accountability Office

Report to Congressional Requesters

September 2014

OCEAN ACIDIFICATION

Federal Response Under Way, but Actions Needed to Understand and Address Potential Impacts

GAO-14-736

GAO Highlights

Highlights of GAO-14-736, a report to congressional requesters

September 2014

OCEAN ACIDIFICATION

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Why GAO Did This Study

Increasing carbon dioxide levels in the atmosphere and oceans are resulting in chemical changes referred to as ocean acidification. These changes may pose risks for some marine species and ecosystems, as well as for the coastal communities that rely on them for food and commerce. FOARAM requires various federal entities to take specific actions related to ocean acidification.

GAO was asked to review federal efforts to address ocean acidification. This report discusses (1) the scientific understanding of the effects of ocean acidification; (2) the extent to which federal agencies have implemented FOARAM; and (3) additional actions, if any, that could be taken to advance the federal response to ocean acidification. To address these issues, GAO reviewed six summary reports on ocean acidification, other scientific studies, and agency documents, and interviewed key agency officials.

What GAO Recommends

GAO recommends the appropriate entities within the Executive Office of the President take steps to improve the federal response to ocean acidification, including estimating the funding that would be needed to implement the research and monitoring plan and designating the entity responsible for coordinating the next steps in the federal response. GAO provided a draft of this report for review and comment to the Executive Office of the President and the departments and agencies reviewed. None of the agencies commented on GAO's recommendations; several provided technical comments that were incorporated, as appropriate.

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What GAO Found

Ocean acidification could have a variety of potentially significant effects on marine species, ecosystems, and coastal communities, according to six summary reports that GAO reviewed. The reports were developed by federal agencies and others and were based on extensive reviews of the scientific literature. The scientific understanding of these effects, however, is still developing, and uncertainty remains about their scope and severity. Potential effects of ocean acidification include:

- Reducing the ability of some marine species, such as oysters, to form shells or altering their physiology or behavior. These impacts could affect some species' growth and survival.
- Altering marine ecosystems, for example, by disrupting predator and prey relationships in food webs and altering habitats.
- Disrupting the economy or culture of some communities, for example, by harming coastal fishing and tourism industries.

The National Science and Technology Council's Subcommittee on Ocean Science and Technology, in the Executive Office of the President, and several federal agencies have taken steps to implement the Federal Ocean Acidification Research and Monitoring Act of 2009 (FOARAM) but have yet to complete some of the act's requirements. For example, an interagency working group, which includes representatives from 11 agencies and is chaired by the Department of Commerce's National Oceanic and Atmospheric Administration, has been established. The working group has developed a research and monitoring plan outlining steps to advance the nation's understanding of, and ability to respond to, ocean acidification. However, the agencies involved have yet to implement several FOARAM requirements, including outlining the budget requirements for implementing the research and monitoring plan. Some agency officials told GAO that not providing budget estimates has prevented the agencies and Congress from accurately understanding the funding needed to implement the plan and how it compares with current funding levels.

Further action could be taken to advance the federal response to ocean acidification. GAO's previous work on interagency collaboration has found that a variety of mechanisms can be used to implement efforts involving multiple federal agencies by helping to facilitate collaboration. One possible approach, recommended by the interagency working group, is to establish an independent national ocean acidification program office to coordinate the next steps in the federal response. The working group, however, has not established such an office because it has been unable to reach agreement on how it should be funded. Until greater clarity is provided on the entity responsible for coordinating the next steps in the federal response to ocean acidification, completing important actions, such as implementing the research and monitoring plan, will be difficult.

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Abbreviations

EPA	Environmental Protection Agency
FOARAM	Federal Ocean Acidification Research and Monitoring Act of 2009
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration

U.S. GOVERNMENT ACCOUNTABILITY OFFICE
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September 12, 2014

The Honorable Mark Begich
Chairman
Subcommittee on Oceans, Atmosphere, Fisheries,
and Coast Guard
Committee on Commerce, Science, and Transportation
United States Senate

The Honorable Robert Menendez
United States Senate

The Honorable Jeff Merkley
United States Senate

The Honorable Sheldon Whitehouse
United States Senate

Scientists estimate that the oceans have absorbed approximately 30 percent of the carbon dioxide emitted by humans over the past 200 years.[1] This increased uptake of atmospheric carbon dioxide is resulting in chemical changes in the oceans, including a decrease in the average *p*H of surface ocean waters and a reduction in the availability of minerals needed by many marine organisms to build shells and skeletons.[2] Collectively referred to as ocean acidification, these chemical changes may pose risks for some marine species and ecosystems, as well as for the human communities that rely upon them for food and commerce. Often referred to as "the other carbon dioxide problem," ocean

[1]National Research Council, *Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean* (Washington, D.C.: 2010).

[2]Acidity is often measured on the *p*H scale, where *p*H equals the negative logarithm of the hydrogen ion concentration. The *p*H scale ranges from 0 to 14. A *p*H of 7 is neutral, a *p*H less than 7 is acidic, and a *p*H greater than 7 is basic or alkaline. Therefore, as *p*H decreases, the acidity of a substance can be said to have increased, even if the substance has a *p*H above 7.

acidification is a distinct issue from climate change[3] but one that stems, in large part, from the same source—carbon dioxide emissions—according to a report that provided technical input to the 2013 National Climate Assessment.[4]

In 2009, the Federal Ocean Acidification Research and Monitoring Act (FOARAM) became law.[5] FOARAM requires, among other things, that:

- The National Science and Technology Council's Subcommittee on Ocean Science and Technology, which is part of the Office of Science and Technology Policy, establish an interagency working group on ocean acidification.[6] The interagency working group is to be composed of senior representatives from the National Oceanic and Atmospheric Administration (NOAA), National Science Foundation, National Aeronautics and Space Administration (NASA), U.S. Fish and Wildlife Service, U.S. Geological Survey, and other federal agencies, as appropriate.
- The Subcommittee on Ocean Science and Technology develop a strategic plan for federal research and monitoring—which we refer to in this report as the research and monitoring plan—to "provide for an assessment of the impacts of ocean acidification on marine organisms and marine ecosystems and the development of adaptation and mitigation strategies to conserve marine organisms and marine ecosystems."
- NOAA conduct interdisciplinary and coordinated research to improve the understanding of ocean acidification, establish a long-term program to monitor ocean acidification, and coordinate monitoring and

[3]The U.S. Global Change Research Program has identified a variety of effects resulting from climate change, including increases in air and water temperatures, changes in precipitation patterns, reduced snow cover, retreating glaciers, and rising sea levels. Jerry M. Melillo, Terese (T.C.) Richmond, and Gary W. Yohe, eds., Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program (2014).

[4]R. Griffis and J. Howard, eds., *Oceans and Marine Resources in a Changing Climate: A Technical Input to the 2013 National Climate Assessment* (Washington, D.C.: Island Press, 2013).

[5]Pub. L. No. 111-11, tit. XII, subtit. D, 123 Stat. 991, 1436 (2009), *codified at* 33 U.S.C. §§ 3701-3708.

[6]The Office of Science and Technology Policy is in the Executive Office of the President.

research activities with appropriate international entities, among other actions.

- The National Science Foundation support research and monitoring of ocean acidification and its impacts.
- NASA ensure that space-based monitoring assets are used for monitoring ocean acidification and its impacts.

Against this backdrop, you asked us to review the federal government's efforts to address ocean acidification. This report discusses (1) the scientific understanding of the effects of ocean acidification; (2) the extent to which federal agencies have implemented FOARAM; and (3) additional actions, if any, that could be taken to advance the federal response to ocean acidification.

To identify the scientific understanding of ocean acidification, we reviewed six summary reports on ocean acidification developed by federal agencies and others.[7] These reports were based on extensive reviews of the scientific literature related to ocean acidification. We identified the reports by reviewing the websites of the National Research Council, NOAA, and the Ocean Carbon and Biogeochemistry program and through discussions with the interagency working group.[8] We reviewed the reports to identify common themes and summarized the reports' findings in four broad areas of scientific inquiry: changes to ocean chemistry, effects on individual species, effects on ecosystems, and socioeconomic effects on coastal communities. To obtain more information and examples to help illustrate the potential effects the reports identified, we examined peer-reviewed scientific articles and interviewed ocean acidification experts, including federal and other

[7]The six reports reviewed were (1) Interagency Working Group on Ocean Acidification, *Strategic Plan for Federal Research and Monitoring of Ocean Acidification* (Washington, D.C.: March 2014); (2) Arctic Monitoring and Assessment Programme (AMAP), *AMAP Assessment 2013: Arctic Ocean Acidification* (Oslo, Norway: 2013); (3) National Research Council, *Review of the Federal Ocean Acidification Research and Monitoring Plan* (Washington, D.C.: 2013); (4) Washington State Blue Ribbon Panel on Ocean Acidification, *Ocean Acidification: From Knowledge to Action, Washington State's Strategic Response*, H. Adelsman and L. Whitely Binder (eds.), Publication no. 12-01-015 (Olympia, WA: 2012); (5) National Research Council, *Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean* (Washington, D.C.: 2010); and (6) NOAA Ocean Acidification Steering Committee, *NOAA Ocean and Great Lakes Acidification Research Plan*, NOAA Special Report (Washington, D.C.: April 2010).

[8]The Ocean Carbon and Biogeochemistry program was established in 2006 as part of the U.S. Carbon Cycle Science Program.

scientists who contributed to the reports. To identify the extent to which federal agencies have implemented FOARAM, we reviewed agency documents and interviewed agency officials to identify (1) actions the federal agencies involved with the interagency working group have taken in response to FOARAM requirements and (2) actions, if any, the agencies plan to take. We also reviewed agency documents and interviewed agency officials to obtain estimates of the agencies' overall expenditures related to ocean acidification. To identify additional actions that could advance the federal response to ocean acidification, we reviewed key agency documents, including the interagency working group's research and monitoring plan and the National Research Council's review of that plan. We also reviewed our earlier work to identify key practices that federal agencies have used in implementing interagency collaborative efforts.[9] In addition, to obtain a broader perspective on agency actions to implement FOARAM and respond to ocean acidification, we interviewed nonfederal stakeholders involved with or interested in ocean acidification issues, including state agencies, conservation groups, and fishing industry groups.

We conducted this performance audit from May 2013 to September 2014 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

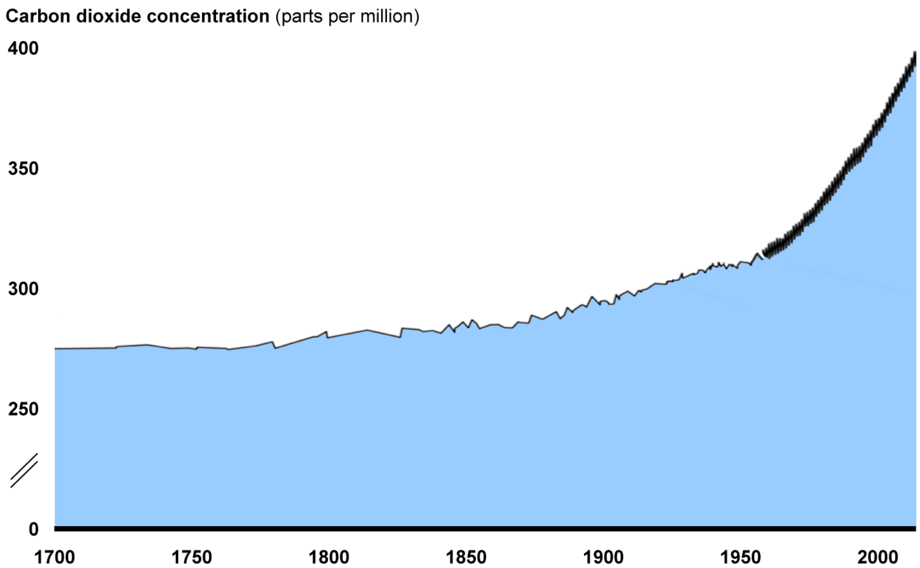
Background

The primary cause of ocean acidification is an increase in carbon dioxide in the oceans that is caused by increasing levels of carbon dioxide in the atmosphere. Human activities—including the burning of fossil fuels, cement production, deforestation, and agriculture—release carbon dioxide into the atmosphere. Since the 1700s, atmospheric carbon dioxide concentrations have risen from approximately 280 parts per

[9]To identify key practices for interagency collaboration, we previously interviewed academic and practitioner experts in the field of collaboration and conducted a detailed analysis of 45 GAO reports, published between 2005 and 2012. See GAO, *Managing for Results: Key Considerations for Implementing Interagency Collaborative Mechanisms*, GAO-12-1022 (Washington, D.C.: Sept. 27, 2012).

million to approximately 400 parts per million (see fig. 1).[10] As the carbon dioxide concentration in the atmosphere increases, more carbon dioxide is absorbed by the oceans, where it reacts with water to form carbonic acid, most of which separates to form a hydrogen ion and a bicarbonate ion.[11] The resulting increase in hydrogen ion concentration is what lowers the *p*H of the water.

Figure 1: Atmospheric Carbon Dioxide Concentration, 1700-Present



Source: Scripps Institution of Oceanography. | GAO-14-736

Note: Data from 1958 to present were measured at Mauna Loa, Hawaii. Data before 1958 were calculated by analyzing the carbon dioxide contained in ice cores.

Since the 1700s, the average surface ocean *p*H has decreased from about 8.2 to 8.1, a change representing an approximately 26 percent

[10]NOAA, *NOAA Ocean and Great Lakes Acidification Research Plan*; Interagency Working Group on Ocean Acidification, *Strategic Plan for Federal Research and Monitoring of Ocean Acidification*.

[11]By absorbing carbon dioxide from the atmosphere, the oceans have helped moderate the effects that increasing atmospheric carbon dioxide levels have had on the Earth's climate. As oceanic carbon dioxide levels increase, however, the ability of the oceans to absorb additional carbon dioxide decreases. National Research Council, *Review of the Federal Ocean Acidification Research and Monitoring Plan.*

increase in ocean acidity.[12] At the current rate of carbon dioxide emissions, scientists project that, by 2100, the average *p*H of the ocean surface will drop to between 7.9 and 7.7.[13] Such a drop would correspond to a rise in acidity of approximately 100 percent to 200 percent over preindustrial levels. Moreover, the current rate of acidification is believed to be faster than at any point in at least the last 20 million years.[14]

In addition to increasing acidity, the higher levels of carbon dioxide in the oceans also cause chemical reactions that reduce what is known as the "saturation state" of calcium carbonate minerals such as aragonite and calcite.[15] As the saturation state of these carbonate minerals decreases, some marine organisms will need to use more energy to acquire the carbonate ions needed to build shells or skeletons. In addition, when the saturation state drops below 1 (i.e., undersaturated), then structures such as animal shells that are made of carbonate minerals may begin to dissolve. As the oceans absorb more carbon dioxide, scientific models predict that the saturation state of many surface waters, including areas supporting rich fisheries, will continue to decline (see fig. 2).

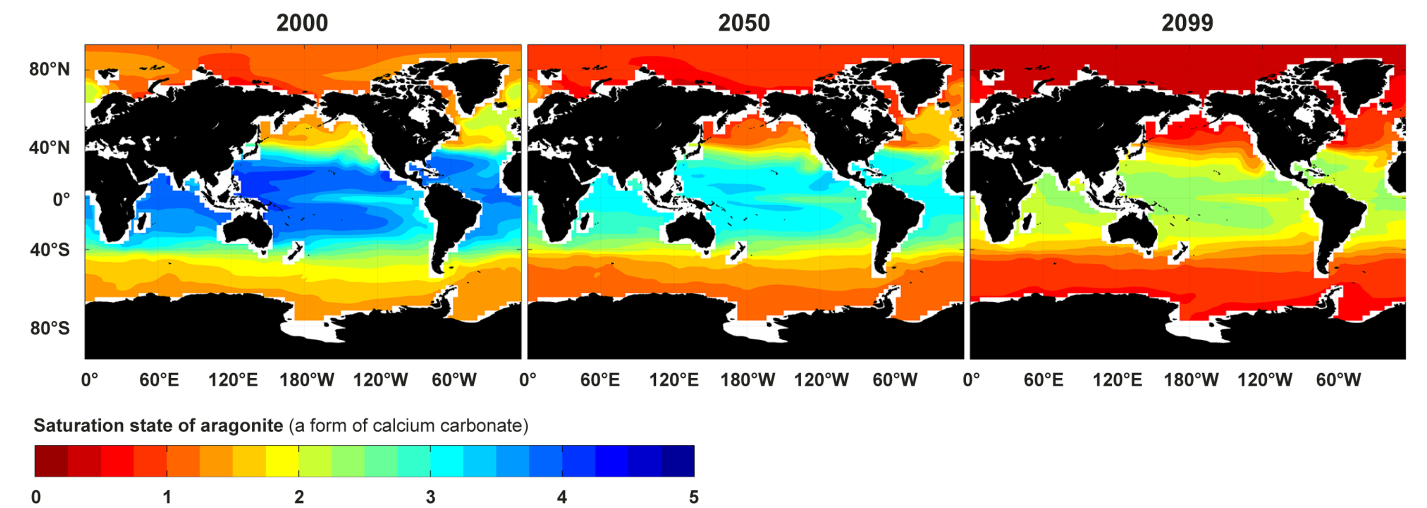
[12]Because *p*H is expressed on a logarithmic scale, a small change in *p*H may represent a large change in acidity. National Research Council, *Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean*.

[13]National Research Council, *Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean*; Washington State Blue Ribbon Panel on Ocean Acidification, *Scientific Summary of Ocean Acidification in Washington State Marine Waters* (Olympia, WA: November 2012).

[14]Interagency Working Group on Ocean Acidification, *Strategic Plan for Federal Research and Monitoring of Ocean Acidification.*

[15]When carbon dioxide enters the ocean, it reacts with water to form carbonic acid, most of which separates to form hydrogen ions and bicarbonate ions. Some of the hydrogen ions released as a result of this reaction subsequently react with carbonate ions present in the ocean to form additional bicarbonate ions; this process decreases the carbonate ion concentration in the water and thus reduces the saturation state of calcium carbonate minerals.

Figure 2: Modeled Aragonite Saturation State of Surface Oceans, 2000-2099



Source: Katherine Spencer Joyce, adapted from Richard A. Feely, Scott C. Doney, and Sarah R. Cooley ©Woods Hole Oceanographic Institution. | GAO-14-736

The carbonate mineral saturation state is affected by several other factors in addition to carbon dioxide. For example, the temperature, pressure, and salinity of the ocean water at a particular location affects the saturation state. As a result, the latitude of a particular ocean location, the depth of the water there, and the extent to which it receives freshwater input from rivers all play a role in determining the saturation state. In general, saturation state is highest in warm, shallow, saline waters. Therefore, the Arctic Ocean, which has colder water and receives large amounts of fresh water from rivers and melting ice, and deepwater environments generally have naturally lower saturation states.

Biological processes also affect the *p*H and saturation state of the oceans. During the day, marine plants, including phytoplankton and seagrasses, use sunlight and carbon dioxide to create and store energy, a process known as photosynthesis.[16] This activity reduces carbon dioxide levels, thus increasing the *p*H and carbonate mineral saturation states of the upper reaches of the ocean. Conversely, as organic (i.e.,

[16]Phytoplankton, also known as microalgae, are microscopic marine plants that produce much of the world's oxygen. Most phytoplankton are buoyant and float in the upper part of the ocean, where sunlight penetrates the water.

carbon-based) matter decomposes, carbon dioxide is released back into the water, thus decreasing *p*H. Some of the decomposing organic matter sinks into deeper water, which, over time, has contributed to deeper waters naturally being lower in *p*H and having lower saturation states with respect to calcium carbonate minerals.[17]

The effect of biological processes on ocean chemistry also means that *p*H and saturation states vary more widely in coastal and estuarine waters than in the open ocean. Coastal and estuarine areas have high concentrations of plant life and receive freshwater inputs from rivers, factors that influence ocean chemistry. The resulting variation may occur both daily, because of the effect of photosynthesis, and seasonally, due to changes in the amount of available solar energy and of river flows.

Although the primary cause of ocean acidification is the increase in global atmospheric carbon dioxide emissions, other factors also contribute to acidification, particularly in coastal and estuarine areas. In particular, increased nutrient pollution (e.g., of nitrate, phosphate, and iron) from agricultural fertilizers and from septic systems and sewage treatment plants results in higher than normal levels of biological growth, a condition known as "eutrophication." In the short run, the faster growth of plants such as phytoplankton may raise the *p*H of coastal and estuarine waters by consuming carbon dioxide in the water and releasing oxygen. In the long run, however, when plants die, the decomposition process releases carbon dioxide and may lower the *p*H, sometimes substantially.[18] In addition, local sources of air pollution may also contribute to acidification in coastal and estuarine areas. For example, in addition to releasing carbon dioxide into the atmosphere, the burning of fossil fuels releases other gases such as nitrogen oxides and sulfur oxides that can be

[17]In some locations, such as the West Coast of the United States, these deeper waters with lower *p*H and carbonate mineral saturation states can be brought back to the surface through a natural phenomenon known as coastal upwelling. Although upwelling is a natural condition, ocean acidification is causing the *p*H and saturation states of upwelled waters to be lower than they would otherwise be.

[18]Under certain conditions, the decay of plants and other organic matter can deplete oxygen in the water faster than it can be replaced through photosynthesis, resulting in a condition known as hypoxia—creating areas of the ocean commonly referred to as dead zones.

deposited on coastal and estuarine waters, or on streams and rivers flowing into coastal waters, lowering the *p*H.[19]

The Scope and Severity of Ocean Acidification's Effects Are Potentially Significant but Not Fully Known

Ocean acidification could have a variety of potentially significant effects on marine species, ecosystems, and coastal communities, according to the six summary reports we reviewed. However, the scientific understanding of these effects is still developing, and there remains uncertainty about their scope and severity.

Ocean Acidification Could Hamper the Ability of Some Species to Form Shells and May Have a Variety of Other Potential Effects on Species

Calcifying species—that is, species that produce shells and skeletons composed of calcium carbonate minerals—are expected to be among the most vulnerable types of species to ocean acidification. Not all calcifying species, however, are expected to respond the same way to reductions in carbonate ion concentrations resulting from ocean acidification, and some are expected to be more at risk than others. For example:

- **Mollusks.**[20] Ocean acidification could negatively affect the survival and growth of some mollusks—including bivalve species such as oysters and mussels—by making calcification more difficult, according to the summary reports we reviewed. Among bivalve species that have displayed a negative response to ocean acidification, larval and juvenile bivalves may be more susceptible to harm than adult bivalves. For example, according to a 2013 study of Pacific oyster (*Crassostrea gigas*) larvae, during the period of initial shell formation in the early days of an oyster's life, oyster larvae rely primarily on the energy derived from their egg reserves to build their shells because the oysters have not yet developed their primary feeding organ.[21] When exposed to an environment with a lower carbonate ion

[19]Doney et al., "Impact of Anthropogenic Atmospheric Nitrogen and Sulfur Deposition on Ocean Acidification and the Inorganic Carbon System," *Proc. Nat. Acad. SCI*, vol. 104, no. 37 (2007).

[20]Mollusks include bivalves (e.g., oysters, clams, and mussels), gastropods (e.g., snails and abalone), and cephalopods (e.g., octopus and squid).

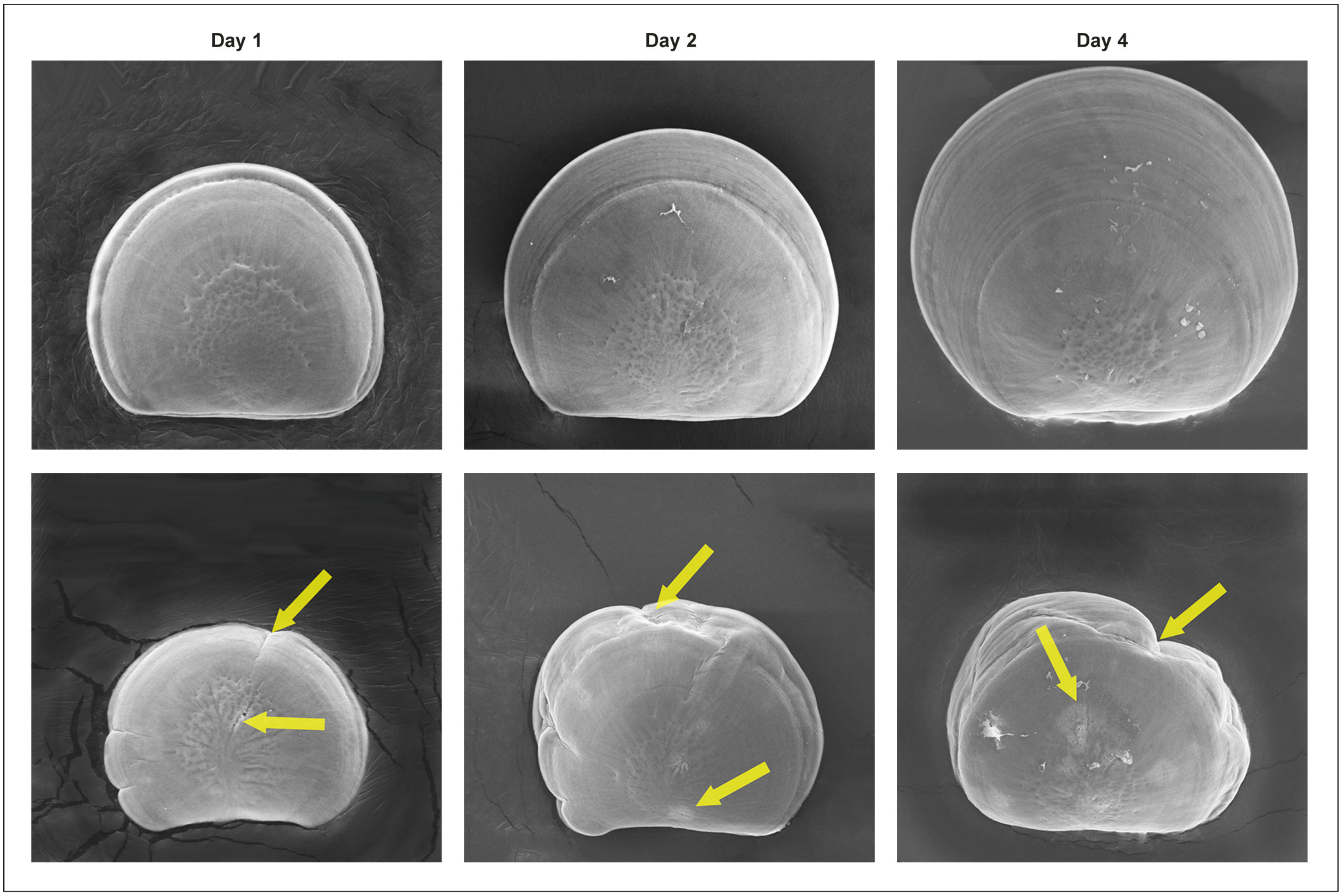
[21]Waldbusser et al., "A Developmental and Energetic Basis Linking Larval Oyster Shell Formation to Acidification Sensitivity," *Geophysical Research Letters*, vol. 40 (May 2013).

concentration, however, the larvae have to expend more energy to build their shells. This increased energy expenditure during the period of initial shell formation makes it more difficult for the oysters to develop their feeding organs and reduces the probability that the oysters will survive.

Figure 3 compares Pacific oyster larvae raised in acidified conditions (characterized by reduced *p*H levels and carbonate mineral saturation states) with those raised under more favorable ocean conditions. The figure shows that the Pacific oyster larvae raised under acidified conditions experienced impaired shell development, and their shells had various deformities compared with the larvae raised under more favorable conditions. Even in instances where oysters are able to survive their larval stage under acidified conditions, the greater energy required to produce their shells could contribute to decreased growth in later life stages. For example, a 2012 study examined the effects of ocean acidification on the Olympia oyster (*Ostrea lurida*) and found that larvae raised in water with a low *p*H (7.8) exhibited a slower shell growth rate that continued even once the oysters became juveniles.[22]

[22]Hettinger et al., "Persistent Carry-over Effects of Planktonic Exposure to Ocean Acidification in the Olympia Oyster," *Ecology*, vol. 93, issue 12 (2012).

Figure 3: Pacific Oyster Larvae Raised under More Favorable Ocean Conditions (Upper) and under Acidified Conditions (Lower)



Source: Elizabeth L. Brunner and George G. Waldbusser. | GAO-14-736

Note: The larvae in the upper and lower rows were raised in waters with a *p*H of approximately 8.0 and 7.5, respectively, and an aragonite saturation state of approximately 1.6 and 0.5, respectively. The yellow arrows show defects (e.g., creases) in the shells and some features (e.g., light patches) of the shells that are suggestive of shell dissolution. Because the process of sampling the larvae is destructive, each larva shown is a different organism and should not be interpreted as the same larva aging through time.

Not all mollusk species have responded negatively to ocean acidification conditions in research experiments, according to the reports we reviewed. One of the reports noted that roughly half of the mollusk species examined have displayed no effects from ocean acidification, and that a few mollusk species have displayed positive effects.[23] For example, one study cited in the report found that mortality rates declined for juveniles of one clam species (*Ruditapes decussatus*) kept in seawater with artificially lowered *p*H levels compared with juveniles kept in seawater at higher *p*H levels.[24]

- **Corals.** Corals were also identified in the summary reports we reviewed as being among the calcifying species most at risk for harm from ocean acidification.[25] Ocean acidification may make it more difficult for some corals to grow their skeletons due to the reduced carbonate ion concentration and may affect coral reproduction. In addition, ocean acidification could potentially increase the rate at which coral skeletons dissolve and erode. However, not all coral species are expected to be negatively affected by ocean acidification, according to the reports we reviewed.

Ocean acidification may also change other aspects of species physiology and behavior, but the summary reports we reviewed noted that uncertainty remains about the exact effect these changes will have on different individual species. For example, changes in ocean *p*H could affect chemical processes within marine organisms, such as the ability of organisms to regulate their internal *p*H levels.[26] Some species may struggle to control their internal *p*H levels in waters with higher carbon dioxide levels or may need to expend more energy to do so, which could lead to slower growth or otherwise compromise the health of organisms. In addition, the reports highlighted the possibility that ocean acidification

[23]Arctic Monitoring and Assessment Programme, *AMAP Assessment 2013: Arctic Ocean Acidification*.

[24]The artificially lowered *p*H levels examined in this study were approximately 7.8 and 7.5, whereas the higher *p*H level was approximately 8.1 to 8.2. See Range et al., "Calcification, Growth and Mortality of Juvenile Clams *Ruditapes decussatus* Under Increased pCO_2 and Reduced *p*H: Variable Responses to Ocean Acidification at Local Scales?" *Journal of Experimental Marine Biology and Ecology*, vol. 396 (2011).

[25]In 2012, the National Marine Fisheries Service proposed listing more than 60 coral species as threatened or endangered under the Endangered Species Act due, at least in part, to the threat posed by ocean acidification. In August 2014, the National Marine Fisheries Service announced it would list 20 species as threatened.

[26]Internal *p*H levels are tightly controlled within organisms because many metabolic processes are regulated by small shifts in internal *p*H. Ocean acidification can disrupt this internal balance in some organisms by causing them to absorb increasing amounts of dissolved carbon dioxide from the water, which can raise the acidity of an organism's internal fluids unless it is able to adjust the *p*H back to optimal levels.

could cause behavioral changes in some fish species by interfering with the functioning of sensory systems, such as the ability to smell. Such changes in sensory systems could, in turn, produce behavioral changes that alter predator-prey interactions, among other things. For example, one study cited in two of the summary reports we reviewed found that clownfish larvae raised in an elevated carbon dioxide environment became attracted to the scent of predators rather than avoiding this odor, whereas clownfish larvae raised under carbon dioxide conditions similar to the current environment exhibited a strong avoidance to the odor of predators.[27] Similarly, another study found that juvenile damselfish and cardinalfish living in ocean waters with naturally high carbon dioxide levels—caused by nearby volcanic vents that emit carbon dioxide and lower the *p*H of surrounding waters—were attracted to predators' odors and exhibited bolder behavior than fish from ocean waters that were unaffected by the volcanic vents.[28] To the extent these types of behavioral changes cause species to be at a higher risk from predators, such changes could potentially lead to increased mortality rates for affected species. However, according to the reports we reviewed, the extent to which other fish species—including commercially important fish such as salmon—are vulnerable to behavioral effects caused by changes in the functioning of sensory systems due to ocean acidification is unclear.

Another way in which ocean acidification could affect marine species is by enhancing photosynthetic processes in ocean waters with elevated carbon dioxide concentrations. In particular, the possibility that some marine plant species, such as certain seagrasses, could experience increased photosynthesis and growth was highlighted by the summary reports we reviewed as a primary example of the potential for ocean acidification to benefit some species. However, this type of beneficial effect appears to be variable among photosynthetic species, and the net effect of ocean acidification on some marine photosynthetic species could be negative. For example, the reports we reviewed noted that marine macroalgae (seaweeds) are expected to display a diverse response to

[27]Munday et al., "Replenishment of Fish Populations Is Threatened By Ocean Acidification," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 107, no. 29 (2010).

[28]Munday et al., "Behavioural Impairment in Reef Fishes Caused By Ocean Acidification at CO_2 Seeps," *Nature Climate Change*, vol. 4, no. 6 (2014).

ocean acidification, in part because macroalgae include a mix of calcifying and noncalcifying species. Since ocean acidification may reduce calcification abilities, the growth of calcifying macroalgae may be compromised under future ocean acidification conditions even if these species experience increased photosynthesis, whereas the growth of noncalcifying macroalgae is more likely to be enhanced. For instance, in a study cited in one of the reports we reviewed, researchers examined the abundance of calcifying versus noncalcifying species of macroalgae near volcanic vents in the ocean and found that the abundance of noncalcifying macroalgae increased as the *p*H declined, whereas the abundance of calcifying macroalgae decreased.[29]

The presence of other stressors in the marine environment—such as warming ocean temperatures, hypoxia, and pollution—were highlighted in the summary reports we reviewed as factors that make it difficult to determine how ocean acidification will affect different species. Knowledge about the simultaneous effects of ocean acidification and these other stressors on species is incomplete, but these stressors could potentially exacerbate the effects of ocean acidification. For example, a recent study found that the combined effects of hypoxia and ocean acidification were more severe on early life stage bivalves than would be expected for either stressor on its own.[30] Similarly, in the case of coral, the reports we reviewed stated that ocean acidification may compromise the resiliency of corals to the other threats they face, such as increased ocean temperatures, by, for example, causing some coral species to be more susceptible to coral bleaching.[31]

Another factor that the reports we reviewed identified as contributing to the uncertainty about the scope and severity of ocean acidification's

[29]Lucia Porzio, Maria Cristina Buia, and Jason M. Hall-Spencer, "Effects of Ocean Acidification on Macroalgal Communities," *Journal of Experimental Marine Biology and Ecology*, vol. 400 (2011).

[30]Hypoxia is a condition where waters have low dissolved oxygen concentrations. Gobler et al., "Hypoxia and Acidification Have Additive and Synergistic Negative Effects on the Growth, Survival, and Metamorphosis of Early Life Stage Bivalves," *PLoS ONE*, vol. 9, issue 1 (January 2014).

[31]Coral bleaching occurs when corals that are stressed by changes in their environment (such as changes in temperature, light, or nutrients) expel the algae living in their tissues, causing the coral to turn white. Bleaching places corals under increased stress and can lead to greater mortality.

effects on different species is the potential for species to adapt to changes in ocean chemistry. In this context, adaptation refers to the ability of a species to evolve over successive generations to become better suited to its habitat, which in the case of ocean acidification would mean a reduced carbonate ion, lower *p*H ocean environment. If species are successful in adapting genetically to these changing conditions, it could be possible for them to avoid some of the negative effects that might otherwise occur from ocean acidification. For example, one of the summary reports we reviewed noted that it might be possible for some coral species to evolve a mechanism that would enable them to calcify at normal rates even in waters with lower carbonate ion concentrations, although this type of adaptation has not been documented in corals.[32] Moreover, since the changes to ocean chemistry currently taking place are occurring rapidly on evolutionary timescales, the reports we reviewed stated that it is unknown whether species will be able to adapt to the expected rate and magnitude of ocean acidification's changes.

Ocean Acidification May Pose Risks to Food Webs or Otherwise Disrupt Marine Ecosystems

The potential for ocean acidification to alter marine food webs was identified in the reports we reviewed as one of the most significant ecosystem-level effects that could result from ocean acidification.[33] It is difficult to predict exactly how a change to a species in one part of a food web will affect other species, but if ocean acidification were to negatively affect species at lower levels in a food web, it is possible those negative effects could lead to broader ecosystem effects involving species at higher levels. For example, pteropods—a type of small calcifying sea snail—represent an important component of some marine food webs and were highlighted as potentially being vulnerable in several of the summary reports we reviewed. Among other things, pteropods are an important food source for salmon and other animals such as seabirds and whales. Some pteropods' calcification and growth rates decline as *p*H levels decrease, and their shells can partially dissolve under acidified conditions (see fig. 4). For example, a recent study found a strong relationship between increased shell dissolution in one pteropod species (*Limacina helicina*) and reduced carbonate ion concentrations off the

[32]National Research Council, *Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean*.

[33]A marine food web represents the feeding interactions of organisms within a community, including predator-prey relationships.

West Coast of the United States.[34] The ultimate effect of ocean acidification on pteropod populations is unknown, but if pteropod populations were to decline, there could be cascading effects through the food webs of some marine ecosystems—including those supporting economically important fisheries such as salmon.

Figure 4: Pteropods (*Limacina helicina*) Exposed to Waters with Varying *p*H Levels

Source: © Nina Bednaršek. | GAO-14-736

Note: The white lines on the ribs of the shells are a sign of shell dissolution, according to a National Oceanic and Atmospheric Administration (NOAA) official. The first two photographs are of pteropods that were collected off the West Coast of the United States from ocean waters with *p*H levels of about 8.0 and 7.8, respectively, and an aragonite saturation state of about 1.5 and 1.2, respectively. The photograph on the right is of a pteropod that was exposed in a laboratory experiment to waters with a *p*H level of 7.5 and an aragonite saturation state of about 0.7 for 2 weeks, conditions which a NOAA official said could be present by the end of the century in some ocean waters off the West Coast of the United States.

Similarly, ocean acidification could negatively affect some phytoplankton species, according to the reports we reviewed, which in turn could affect marine food webs. Phytoplankton form the base of marine food webs and are eaten by a variety of marine species, including invertebrates and fish, which are then eaten by larger animals. The reports we reviewed noted that studies have found that phytoplankton have displayed diverse responses to ocean acidification. Phytoplankton include a mix of calcifying and noncalcifying species, and studies have shown ocean acidification could cause changes in some phytoplankton species' growth and calcification rates, among other things. However, the exact nature of

[34]Bednaršek et al., "*Limacina Helicina* Shell Dissolution as an Indicator of Declining Habitat Suitability Owing to Ocean Acidification in the California Current Ecosystem," *Proc. R. Soc. B*, vol. 281 (2014).

these changes varied in the studies, with some phytoplankton species experiencing reduced growth and calcification under acidified conditions, and other phytoplankton species experiencing enhanced growth and calcification. Consequently, it is unclear exactly what effect ocean acidification will have on phytoplankton communities or the extent to which any changes to phytoplankton that occur will disrupt marine food webs.[35]

There are different types of marine ecosystems, and ocean acidification may affect them in different ways. The summary reports we reviewed highlighted potential effects that may occur in certain ecosystems, including:

- **High latitude ecosystems.** High latitude ecosystems, such as those in the Arctic, are expected to be among the most susceptible to ocean acidification.[36] A number of factors contribute to this vulnerability. Because atmospheric carbon dioxide is more soluble in cold water, high latitude oceans naturally have lower carbonate mineral saturation states than lower latitude oceans. In addition, a reduction in the extent of sea ice cover has exposed more high latitude ocean area to the atmosphere, increasing the amount of carbon dioxide it can absorb. Increased freshwater input from melting ice also contributes to reducing the carbonate ion concentrations. In addition, high latitude ecosystems, which include some of the richest fishing areas in the world, could also be affected by potential disruptions to food webs caused by ocean acidification.
- **Coastal ecosystems.** Ocean acidification could affect coastal ecosystems in a variety of ways, including affecting food webs and the availability of certain types of habitat. Some coastal ecosystems may be more susceptible to the effects of ocean acidification than others, due to variations in local conditions such as coastal upwelling and

[35]Some phytoplankton species also produce toxins that are harmful to marine organisms and humans. Under certain conditions, the populations of these phytoplankton can grow quickly, resulting in harmful algal blooms that can affect marine food webs and ecosystems. Ocean acidification could increase the toxicity of some of the phytoplankton species that cause such blooms.

[36]For additional information on environmental issues in the Arctic and the participation of the United States in an intergovernmental forum known as the Arctic Council, please refer to GAO, *Arctic Issues: Better Direction and Management of Voluntary Recommendations Could Enhance U.S. Arctic Council Participation*, GAO-14-435 (Washington, D.C.: May 16, 2014).

nutrient pollution. Any changes that occur to marine food webs or habitats due to ocean acidification could lead to shifts in the composition of species in different coastal ecosystems, although the exact nature of any shifts that may occur remains unclear. For example, ocean acidification could lead to increased abundance of seagrass beds and some macroalgae species, which could benefit fish species that prefer these habitats. However, in situations where different types of habitat compete with each other for space, the expansion of one type of habitat due to ocean acidification could harm competing habitats and any species that rely on them.

- **Coral reef ecosystems.** Ocean acidification poses potential risks to coral reefs, for example, by reducing carbonate mineral saturation states, which could reduce their resilience and contribute to declines in the size or structural complexity of some coral reefs in the future.[37] Coral reefs provide shelter and habitat for a wide variety of other species and thus are an important contributor to marine biodiversity. If ocean acidification were to result in the reduction of coral reef habitat, fish and other species that rely on this habitat could be adversely affected.

The general level of uncertainty about ocean acidification's effects on ecosystems is even greater than the uncertainty about the effects on individual species, according to the reports we reviewed. Because of the uncertainty about ocean acidification's effects on species, it is difficult to model the potential effects and determine how they will propagate through ecosystems. Furthermore, the challenge of determining ocean acidification's effects on ecosystems is compounded by the effects of other marine stressors—such as warming temperatures, hypoxia, and pollution—that are simultaneously occurring in the oceans and will interact with ocean acidification to affect ecosystems in ways that are not fully understood.

[37]Many coral species are colonial, meaning that many individual organisms live closely together, in some cases forming extensive reef systems.

Ocean Acidification's Effects May Cause Economic and Cultural Disruptions to Some Communities

The effects of ocean acidification on marine species and ecosystems may affect the goods and services they provide, which may cause economic disruptions, according to the summary reports we reviewed.[38] For example:

- **Shellfish harvest and aquaculture.** Shellfish harvest is the most valuable sector of the commercial fishing industry in the United States, accounting for 53 percent of U.S. commercial fishing landings and valued at approximately $2.7 billion in 2012, according to NOAA.[39] In addition, NOAA reported that the approximate value of shellfish produced by aquaculture in the United States in 2011 was $422.0 million.[40] Potential declines in the health of shellfish populations from ocean acidification could negatively affect both shellfish harvest and aquaculture. Oyster aquaculture has already experienced significant disruption in the Pacific Northwest. The Washington State Blue Ribbon Panel on Ocean Acidification reported that, between 2005 and 2009, acidified conditions killed billions of oyster larvae at two of the three primary hatcheries that provide Pacific oysters to growers in the Northwest, disrupting the industry throughout the region.[41] A representative from one of the affected hatcheries said that the hatcheries—assisted by federal and state agency efforts to improve monitoring of ocean chemistry—have been able to change the systems that bring seawater into their hatcheries to avoid particularly low *p*H levels. Nonetheless, both the hatchery and agency officials we spoke with expressed concern that future ocean conditions could exceed the hatcheries' ability to adapt. Similarly, crab harvest constitutes an important component of the fishing industry in Alaska, and recent research suggests that some juvenile crab species are less able to survive in lower *p*H waters, which could lead to

[38]Marine ecosystems provide a variety of goods (such as fish and other organisms harvested for food) and services (including providing storm protection and recreation opportunities) that could be affected by ocean acidification.

[39]Landings represent fish that are caught at sea and processed for consumption. The value reported represents the "ex-vessel" value of the landings, which refers to prices paid to fishermen for raw product.

[40]Aquaculture—also known as fish or shellfish farming—refers to the breeding, rearing, and harvesting of animals and plants in all types of water environments including ponds, rivers, lakes, and the ocean.

[41]Washington State Blue Ribbon Panel on Ocean Acidification, *Ocean Acidification: From Knowledge to Action, Washington State's Strategic Response*.

declines in an industry that, in the Bering Sea and Aleutian Islands, harvested crabs valued at approximately $245 million annually, on average, from 2008 through 2012.[42]

- **Finfish harvest.** As with shellfish, potential future declines in the health of finfish populations from ocean acidification could negatively affect their harvest, which NOAA reported was valued at approximately $2.4 billion in 2012. Finfish—including those that are important components of commercial marine fisheries such as salmon, pollock, and cod—may be directly affected by ocean acidification. In addition, if ocean acidification changes marine food webs or habitat—such as coral and oyster reefs—that are important to finfish reproduction, growth, and survival, the finfish industry could also be affected.
- **Tourism and recreation.** Marine ecosystems also generate important economic and social benefits from tourism and recreation that may be at risk from ocean acidification. Recreational saltwater fishing contributed approximately $17.5 billion to the U.S. gross domestic product in 2011, including money spent on food, lodging, and transportation, according to an estimate by an industry trade association.[43] In addition, NOAA has reported that millions of people visit coral reefs to dive, snorkel, and sightsee, contributing significantly to local economies in Florida, Hawaii, and many U.S. territories. If ocean acidification leads to declines in the health of marine ecosystems, the economic and social benefits from marine tourism and recreation could also decline.
- **Storm protection.** Certain marine ecosystems, such as coral and oyster reefs, help protect coastal communities from flooding caused by hurricanes and other storms, thereby reducing the damage and social disruption that can accompany such storms. If ocean acidification harms such ecosystems, the storm protection benefits they provide could decline.

The expected effects of ocean acidification may disproportionately affect some regions and communities that are strongly connected economically

[42]Long et al., "Effects of Ocean Acidification on Juvenile Red King Crab (*Paralithodes camtschaticus*) and Tanner Crab (*Chionoecetes bairdi*) Growth, Condition, Calcification, and Survival," *PLoS ONE*, vol. 8, issue 4 (April 2013); Punt et al., "Evaluating the Impact of Ocean Acidification on Fishery Yields and Profits: The Example of Red King Crab in Bristol Bay," *Ecological Modeling*, vol. 285 (2014).

[43]American Sportfishing Association, *Sportfishing in America: An Economic Force for Conservation* (Alexandria, VA: January 2013).

and/or culturally to the goods and services provided by marine ecosystems. For example:

- Fisheries are important in both New England and on the West Coast, but one economic study estimated that potential revenue losses due to ocean acidification would be four times higher in New England, due to the significance of the shellfish harvest to the local economy.[44] Moreover, some communities may be disproportionately affected. For example, in recent years, New Bedford, Massachusetts, has been the U.S. port with the highest value of fish landed, largely due to its scallop fishery. The study concluded that a decline in scallop revenue due to ocean acidification would further depress a community that has struggled economically. Similarly, shellfish aquaculture operations are major employers in Pacific and Mason counties in Washington State; consequently, if ocean acidification harms shellfish aquaculture, it could have a significant economic impact on these communities.
- Harvesting fish and shellfish is an important element in many tribal communities for economic, dietary, and cultural reasons. Many tribal communities in Washington State view ocean acidification both as an economic issue and, because salmon and shellfish are important ceremonial foods, as a threat to their identity and cultural survival, according to one of the summary reports we reviewed.[45]
- In some coastal communities, harvesting marine resources is not just an economic activity but "a way of life." For example, commercial fishing not only provides household income but also is intertwined with how families, generations, and the community as a whole interact with each other and with nature, according to one of the summary reports we reviewed.[46]

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

[45]Interagency Working Group on Ocean Acidification, *Strategic Plan for Federal Research and Monitoring of Ocean Acidification*.

[46]Interagency Working Group on Ocean Acidification, *Strategic Plan for Federal Research and Monitoring of Ocean Acidification*.

Federal Agencies Have Taken Steps to Implement FOARAM but Have Yet to Complete Certain Requirements

Federal agencies have taken a variety of steps to implement FOARAM and to support the federal response to ocean acidification more broadly.[47] However, the agencies have yet to complete other FOARAM requirements.

An Interagency Working Group Has Developed a Research and Monitoring Plan, and Individual Agencies Have Taken Steps to Implement FOARAM

The Subcommittee on Ocean Science and Technology implemented the FOARAM requirement to establish an interagency working group and subsequently delegated responsibility for developing the required research and monitoring plan to the working group. NOAA, the National Science Foundation, and NASA—the three agencies required by FOARAM to take specific actions related to ocean acidification outside of the working group—have also taken steps to implement those requirements. In addition, the other federal agencies that are part of the interagency working group have taken steps to support the federal response to ocean acidification (see app. I). The agencies participating in the interagency working group have estimated that from fiscal year 2010, the fiscal year after FOARAM was enacted, through fiscal year 2013 they have spent approximately $88 million ($22 million annually, on average) on activities directly related to ocean acidification (see app. II).

An Interagency Working Group Has Been Established and Developed a Research and Monitoring Plan

The interagency working group on ocean acidification is composed of senior representatives from 11 federal agencies involved in responding to ocean acidification. FOARAM specified five agencies—NOAA, the National Science Foundation, NASA, U.S. Fish and Wildlife Service, and U.S. Geological Survey—as well as “other federal agencies as appropriate,” to be part of the working group. In addition to the agencies specified in the act, as of August 2014, six agencies with missions that could be affected by ocean acidification—the Bureau of Ocean Energy Management, Department of Energy, Department of State, Environmental Protection Agency (EPA), U.S. Department of Agriculture, and U.S.

[47] In this report, unless otherwise noted, we use the term “the agencies” to refer to the interagency working group, the working group’s 11 member agencies, and the Subcommittee on Ocean Science and Technology.

Navy—have also joined the working group.[48] Since January 2010, the interagency working group, which is chaired by NOAA and vice-chaired by NASA and the National Science Foundation, has met approximately quarterly.

One of the primary tasks of the interagency working group has been to guide the development of a research and monitoring plan, which FOARAM required to be developed by March 2011.[49] That plan, which was approved by the Office of Science and Technology Policy and released to the public in March 2014, outlines key efforts identified by the interagency working group that need to be taken over the next 10 years to advance the nation's understanding of, and ability to respond to, ocean acidification.[50] The plan discusses the following:

- **Research to understand ocean acidification.** The plan stated that more research is needed to better understand and be able to predict (1) changes to ocean chemistry, (2) the impacts of ocean acidification on marine species and ecosystems, and (3) the capacity of organisms to acclimate or adapt to the changes to ocean chemistry. The plan's goals include (1) quantifying changes in diverse types of organisms, including commercially or culturally important species, caused by ocean acidification and its interaction with other stressors and (2) investigating the potential of organisms to acclimate to, or evolve to adapt to, acidified conditions.
- **Monitoring of ocean chemistry and biological impacts.** The plan stated that a coordinated, multidisciplinary, multinational approach to monitoring ocean chemistry and the biological impacts of ocean

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[48]According to the chair of the interagency working group, the Department of Energy joined the working group in July 2014. Because our review was almost complete at that time, this report does not discuss the Department of Energy's activities.

[49]The working group has also issued two reports, required by FOARAM, describing federal actions related to ocean acidification research and monitoring. The first report was required to be issued by March 2010 and the second to be issued two years later. The first report was issued in March 2011 and the second in 2013. Interagency Working Group on Ocean Acidification, *Initial Report on Federally Funded Ocean Acidification Research and Monitoring Activities and Progress in Developing a Strategic Plan* (Washington, D.C.: March 2011), and *Second Report on Federally Funded Ocean Acidification Research and Monitoring Activities and Progress on a Strategic Research Plan* (Washington, D.C.: 2013).

[50]Interagency Working Group on Ocean Acidification, *Strategic Plan for Federal Research and Monitoring of Ocean Acidification*.

acidification on species and ecosystems is needed to determine the magnitude and extent of acidification and to advance research. The plan's goals include evaluating existing ocean monitoring systems that could be expanded to monitor ocean acidification (e.g., by adding new sensors) and identifying regions where new monitoring systems may be warranted.

- **Modeling to predict changes in ocean chemistry and impacts on marine ecosystems and organisms.** The plan stated that models are needed to help predict likely changes to ocean chemistry and marine ecosystems resulting from ocean acidification and to provide information that can inform resource management decisions (e.g., decisions related to managing fisheries). The plan's goals include developing and improving models that can be used to predict direct and indirect effects of ocean acidification on culturally, economically, and ecologically important species.
- **Technology development and standardization of measurements.** The plan stated that new technologies and standardization of measurements are required to support research and monitoring. The plan's goals include (1) developing standardized methodologies for measuring how plants and animals respond to ocean acidification and (2) improving the accuracy and affordability of monitoring equipment.[51]
- **Assessment of socioeconomic impacts and development of adaptation and mitigation strategies.** The plan stated that better understanding the social and economic effects of ocean acidification can help inform discussions about how society can adapt to it and mitigate its causes. The plan's goals include developing models to estimate the economic effects of ocean acidification and assisting national, state, and local governments and businesses to develop adaptation plans.
- **Education, outreach, and engagement.** The plan recognized the importance of effective outreach and education to improve awareness of the potential effects of ocean acidification and to engage stakeholders (e.g., nongovernmental organizations, fishing industry representatives, and natural resource managers) and the public in a discussion of policy options for responding to acidification. The plan's

[51]Some scientists have noted that the accuracy and affordability of the monitoring equipment used to measure ocean *p*H need to be improved. In 2013, XPRIZE, a nongovernmental organization, citing concerns about ocean acidification, announced a $2 million competition to improve the accuracy and affordability of equipment to measure ocean *p*H.

goals include engaging federal and academic partners to develop and implement outreach programs.

- **Data management and integration.** The plan stated that the success of the federal response to ocean acidification depends on effective data management and recognized that it is critical that data be shared and integrated across organizational boundaries and blended from diverse information systems. The plan's goals include establishing a program or office to manage ocean acidification data collection and determining how the data will be archived and accessed.

NOAA Has Established an Ocean Acidification Program

NOAA formally established an ocean acidification program, required by FOARAM, in May 2011. The program is staffed by a director and two to three other staff and is overseen by an executive board consisting of senior officials from the four NOAA offices involved in ocean acidification.[52] Because of the number of NOAA offices involved, a primary responsibility of the ocean acidification program is to coordinate all of NOAA's actions related to ocean acidification. It also coordinates and collaborates with other agencies, stakeholders, and researchers, both within and outside of the United States.

NOAA ocean acidification program officials estimated they spent approximately $6 million annually, on average, between fiscal year 2011 and fiscal year 2013, to support the types of activities envisioned in the interagency working group's research and monitoring plan. Program officials estimated that the program has directed about 50 percent of its funds towards ocean acidification monitoring and about 20 percent toward research on species' responses to acidification, with the remainder aimed at improving scientific models of acidification, data management, and other activities. Examples of program actions include:

- **Improving ocean acidification monitoring capabilities.** NOAA has taken steps to address FOARAM's requirement to establish a long-term ocean acidification monitoring program. For example, the agency is working with state agencies and regional stakeholders, including regional associations of the Integrated Ocean Observing System, to identify (1) locations where additional monitoring capabilities would be

[52]NOAA has five line offices that are primarily responsible for executing the agency's mission. Four of these offices— the National Environmental Satellite, Data, and Information Service; National Marine Fisheries Service; National Ocean Service; and Office of Oceanic and Atmospheric Research—are involved in the agency's activities related to ocean acidification.

useful and (2) opportunities for adding ocean acidification monitoring equipment to locations where other monitoring equipment already exists.[53] NOAA's ocean acidification program, often in conjunction with state agencies and others, has also helped fund deployment of new monitoring assets in some locations, but the director of the program told us that funding levels have hindered the agency's ability to further expand monitoring networks. NOAA has also taken steps to address FOARAM's requirement to coordinate its monitoring activities with international partners. For example, NOAA, along with international partners and others, has sponsored workshops to, among other goals, develop consensus within the international scientific community on the chemical, physical, and biological variables that an ocean acidification monitoring network should measure and on data collection protocols to ensure appropriate data quality and comparability.[54] The workshops also identified factors hindering development of a monitoring network, including, for example, limitations in the quality of existing monitoring equipment.

- **Researching species' responses to ocean acidification.** The ocean acidification program has helped fund research on how a variety of species respond to ocean acidification. For example, the program has supported research conducted at three NOAA fisheries science centers on a number of different species of economic importance, including king crab and walleye pollock in Alaska, oysters and geoduck clams in the Northwest, and scallops and surf clams in the Northeast. It has also helped fund research on the effects of ocean acidification on species—including phytoplankton, krill, copepods, and forage fish—that are significant components of many marine food webs and thus are important ecologically.
- **Improving modeling capabilities.** The ocean acidification program has also helped fund projects to develop scientific models that project future changes in ocean chemistry due to acidification and the effects those changes might have on particular species or ecosystems. Such models can help scientists project potential economic impacts on particular communities, such as the potential impacts that declining

[53]The Integrated Ocean Observing System is a partnership between 18 federal agencies, 11 regional associations (that include representatives of federal, state, local, and tribal agencies; nongovernmental organizations; and members of academia), and others, and is led by NOAA.

[54]NOAA is the co-chair of the Global Ocean Acidification Observing Network. For more information about this network, see http://www.goa-on.org/.

crab or scallop populations might have on fishing communities in Alaska or New England, respectively.

The National Science Foundation Has Supported Research and Monitoring of Ocean Acidification

To respond to FOARAM's requirements for the agency, the National Science Foundation established ocean acidification research as a specific agency focus for fiscal years 2010 through 2014.[55] During these years, the agency issued four solicitations requesting scientists to submit research proposals related to ocean acidification. Overall, from fiscal year 2010 through fiscal year 2013, the National Science Foundation selected approximately 50 proposals to receive funding and directed an estimated $11 million annually, on average, to ocean acidification research.[56] The projects selected for funding covered diverse aspects of ocean acidification, including (1) changes to ocean chemistry in a variety of locations; (2) effects on the biological, chemical, and physical processes of a variety of marine species; and (3) how the effects on species might affect different ecosystems. Funded projects included examinations of:

- Changes to ocean chemistry during a previous geological period, research that could provide insights into the short- and long-term impacts of human-caused carbon dioxide emissions on surface ocean pH and carbonate chemistry.
- The effects of elevated carbon dioxide levels in the ocean on a pteropod species (*Limacina retroversa*) in the Gulf of Maine that is preyed on by commercially important fish species.
- The effects of elevated ocean carbon dioxide levels on the growth, calcification, and physiology of corals and other species inhabiting a remote coral reef in the Pacific Ocean.

The National Science Foundation has reported that its most recent solicitation, issued in fiscal year 2014, is expected to be the final one requesting research proposals specifically for ocean acidification. A senior agency official told us that the agency would continue to fund ocean acidification research in the context of its overall research program, although likely at a lower level of funding. The official also said that it is

[55] The National Science Foundation is an independent federal agency that supports research across all fields of science and engineering, primarily by awarding grants to researchers at U.S. colleges and universities.

[56] According to a National Science Foundation official, these figures cover the first three solicitations the agency issued; figures for the fourth solicitation, which covered fiscal year 2014, have not yet been finalized.

common for the agency to focus research on a specific issue for a few years and then reintegrate that issue into its overall program.

NASA Has Collected Relevant Data and Supported Research

NASA maintains a system of satellites that collects data on many aspects of the Earth, including on aspects of the global carbon cycle and ocean ecology that are relevant to ocean acidification, and has made its data available to other researchers.[57] It also has provided funding to outside researchers to study ocean acidification. Between 2007 and 2012, the agency issued approximately 10 solicitations for research and provided funding for four research projects, according to an agency official.[58] For example, one project funded by NASA is examining the effects of ocean acidification on ocean chemistry and phytoplankton photosynthesis in the Arctic Ocean.

Agencies Have Yet to Take Action to Implement Several FOARAM Requirements

The agencies have yet to implement the following FOARAM requirements: (1) establish each agency's role in implementing the research and monitoring plan and outline the budget requirements for implementing the plan, (2) establish an ocean acidification information exchange, and (3) develop adaptation and mitigation strategies to conserve marine organisms and ecosystems.

Agency Roles and the Budget Requirements for Implementing the Research and Monitoring Plan Have Not Been Established

The agencies completed the research and monitoring plan required by FOARAM, but that plan does not include all of the required elements. Specifically:

- FOARAM requires the research and monitoring plan to set forth the role of each agency in implementing it, but the plan does not do so. Interagency working group officials told us they expect that additional information on the roles and responsibilities of the agencies will be provided in an implementation plan, which the working group has begun developing, according to its chair. Our previous work on interagency collaborative efforts has found that clarifying the roles and

[57]The global carbon cycle is the process by which carbon is exchanged among various natural systems, including the earth's atmosphere, the oceans, geological sources of stored carbon (e.g., fossil fuels), and the vegetation and soils of the earth's terrestrial ecosystems.

[58]The official told us that the remaining solicitations either did not generate any proposals or the peer review of the proposals received was not favorable enough for the proposals to be selected for funding.

responsibilities of the participating agencies is an important factor in the success of such efforts.[59] Until the specific roles and responsibilities of the agencies are clarified, it will be difficult for the working group and its member agencies to make progress in implementing important actions called for in the research and monitoring plan.

- FOARAM also requires that the research and monitoring plan outline the budget requirements for each agency to implement the plan's research, monitoring, and assessment activities, but the plan does not include them. According to the previous chair of the working group, a high-level estimate of the federal funding needed for each agency to implement the research and monitoring plan was developed during the early drafting of the plan, but this information was excluded from the final plan at the direction of the Office of Management and Budget. Many officials and stakeholders we interviewed said that the level of funding directed to ocean acidification to date has been insufficient given the potential scope and severity of effects expected in the future. Some of the officials expressed concern that excluding budget estimates from the research and monitoring plan has prevented the agencies and Congress from accurately understanding the funding needed to implement the plan and how it compares with current funding levels. Developing and disclosing estimates of the needed funding may be particularly important for efforts involving multiple agencies. In our previous work on interagency collaborative efforts, we reported that effective interagency collaborative efforts require, among other things, the identification of the types and level of resources needed to implement the planned activities.[60]

An Ocean Acidification Information Exchange Has Not Been Established

The interagency working group also has yet to establish an information exchange. FOARAM requires an information exchange be established or designated to make information related to ocean acidification accessible through electronic means.[61] The law does not define the characteristics of an information exchange, but an exchange could, for example, be a single, web-based portal where information on ocean acidification is

[59]GAO-12-1022.

[60]GAO-12-1022.

[61]FOARAM requires the Subcommittee on Ocean Science and Technology to establish or designate an ocean acidification information exchange. The subcommittee delegated this responsibility to the interagency working group on ocean acidification, the group they also tasked with development of the research and monitoring plan.

stored and made available to government officials, researchers, and the public. The chair of the working group told us the group has not established a single exchange but said that information on ocean acidification, including on federal agencies' actions and research results, is available on the working group's and other federal websites.[62] The chair also said she recognized the value of establishing a single exchange but that doing so was a lower priority than other needed actions, such as developing the research and monitoring plan. Nonetheless, it has been more than 5 years since FOARAM was enacted, and some stakeholders we interviewed said that, without establishing a single information exchange, researchers and the public may have difficulty accessing all of the information on ocean acidification that the agencies are developing. In addition, our previous work has found that information technology, such as shared databases and web portals, can be a tool that facilitates interagency collaboration.[63] According to NOAA officials, the National Oceanographic Data Center could serve as a building block for an ocean acidification information exchange.[64]

Adaptation and Mitigation Strategies Have Not Yet Been Developed

The interagency working group has not developed the adaptation and mitigation strategies to conserve marine organisms and ecosystems exposed to ocean acidification that are required by FOARAM.[65] The research and monitoring plan developed by the interagency working group includes a high-level discussion of adaptation and mitigation, but it does not clearly describe adaptation and mitigation strategies.[66] The chair

[62]For more information, see the working group's website, http://oceanacidification.noaa.gov/IWGOA.aspx.

[63]GAO-12-1022.

[64]The National Oceanographic Data Center, operated by NOAA, is a national ocean archive of environmental data, including physical, biological, and chemical measurements derived from observations, satellite remote sensing of the oceans, and ocean model simulations.

[65]FOARAM required the Subcommittee on Ocean Science and Technology to oversee development of adaptation and mitigation strategies to conserve marine organisms and ecosystems exposed to ocean acidification. The subcommittee delegated development of the strategies to the interagency working group on ocean acidification.

[66]FOARAM does not define adaptation or mitigation but, in the context of this discussion, adaptation refers to actions taken to prepare for and adjust to new conditions, thereby reducing harm or taking advantage of new opportunities, and mitigation refers to actions, such as reducing carbon dioxide emissions, taken to reduce the amount or speed of change.

of the working group said that the research and monitoring plan recognizes the importance of these topics but that more research on the effects of ocean acidification needs to be done before appropriate adaptation and mitigation strategies can be fully developed. For example, the research and monitoring plan states that future research on organisms' responses to ocean acidification could assist with developing adaptation strategies. Research could, for instance, identify certain genetic strains in shellfish species that may be more tolerant of acidification, which could help aquaculture operations adapt to more-acidic conditions. Similarly, research on the effects of ocean acidification on species and ecosystems could assist government agencies in developing options for fishery management or assist businesses and communities in adapting to changing conditions in the future. In regard to mitigation, many officials and stakeholders we interviewed said that without timely action to mitigate its root causes, ocean acidification is likely to have significant impacts. The research and monitoring plan identified two approaches to mitigate the causes of ocean acidification: (1) reducing carbon dioxide levels in the atmosphere and (2) reducing the impact of other environmental stressors—such as nutrient runoff pollution—that can exacerbate the effects of acidification.[67] The plan, however, did not provide a strategy for addressing these issues.

[67]Agricultural nonpoint source pollution is a primary source of nutrient pollution in coastal ocean waters and therefore a contributor to ocean acidification. We have previously reported on the challenges EPA faces in addressing nonpoint source pollution and have recommended that Congress consider revising the Clean Water Act's largely voluntary approach to restoring waters impaired by nonpoint source pollution. See GAO, *Clean Water Act: Changes Needed If Key EPA Program Is to Help Fulfill the Nation's Water Quality Goals*, GAO-14-80 (Washington, D.C.: Dec. 5, 2013).

Designating an Entity to Coordinate the Next Steps Could Bolster Federal Efforts to Implement FOARAM and Respond to Ocean Acidification

Further action could be taken to advance the federal response to ocean acidification. Our previous work on interagency collaboration has found that the federal government has used a variety of mechanisms to implement collaborative efforts involving multiple agencies.[68] These mechanisms include, among others, (1) establishing an interagency working group, (2) creating an independent interagency office with its own authority and resources, and (3) designating one or more agencies as the lead for the effort.[69] In some cases, agencies have used more than one mechanism to implement a collaborative effort. Eleven agencies with widely varying missions are contributing to the federal response to ocean acidification. The research and monitoring plan developed by the interagency working group identified a number of goals and priorities to help guide the federal response to ocean acidification, but in many cases it is unclear which agencies will be responsible for taking action to implement them.

The working group has recommended that an independent national ocean acidification program office be established to coordinate the next steps in the federal response.[70] The National Research Council has concurred with this recommendation. Key functions envisioned for the proposed office include:

- facilitating coordination among federal agencies, academic researchers, and other stakeholders;
- developing an implementation plan that outlines the specific actions needed to achieve the goals presented in the research and monitoring plan;
- coordinating U.S. ocean acidification research and monitoring activities with international entities conducting similar work;
- establishing an ocean acidification information exchange; and

[68]GAO-12-1022.

[69]For more information on the challenges facing interagency working groups and implementation approaches agencies have taken to address or avoid them, see GAO, *Managing for Results: Implementation Approaches Used to Enhance Collaboration in Interagency Groups*, GAO-14-220 (Washington, D.C.: Feb. 14, 2014).

[70]The interagency working group's research and monitoring plan identified the U.S. Joint Global Ocean Flux Study and the Climate Variability and Predictability System as other interagency efforts that could serve as models for a national ocean acidification program office.

- developing a comprehensive ocean acidification data management plan.

It is uncertain, however, when, or if, a national program office will be established. According to the former chair of the interagency working group, such an office has not been established because the working group has been unable to reach agreement on how it should be funded. Given the uncertainty about the proposed national program office, some officials we interviewed identified other options that could be pursued, such as designating NOAA as the lead agency to implement the next steps in the federal response and fulfill the functions the working group envisioned for a national program office. Regardless of the option chosen, until there is greater clarity on which entity is responsible for coordinating the next steps in the federal response to ocean acidification, completing important actions, such as implementing the research and monitoring plan, will be difficult.

Conclusions

In response to FOARAM's requirements, an interagency working group including 11 federal agencies has been established and has begun taking steps to better understand and respond to ocean acidification. One important action the working group has taken is the development of an ocean acidification research and monitoring plan, which outlines key efforts needed to advance the nation's understanding of and ability to respond to acidification. However, federal efforts to implement FOARAM are incomplete. Because the research and monitoring plan does not establish each agency's role or the budget needed for implementation, as required by FOARAM, it is unclear to what extent the actions outlined in the plan will be taken. In addition, research results and other information related to ocean acidification are available on various federal websites, but the information has not been consolidated into a single ocean acidification information exchange as required by FOARAM, which may make public access and scientific research more difficult. Finally, the research and monitoring plan lays out a broad scope of work, but an entity has not been designated to coordinate the plan's implementation, or to identify and take whatever additional steps may be needed to help the nation address ocean acidification in the future. Without designating such an entity, federal agencies may struggle to advance the federal response to ocean acidification.

Recommendations for Executive Action

To improve the federal response to ocean acidification, we recommend that the appropriate entities within the Executive Office of the President, including the Office of Science and Technology Policy and the National Science and Technology Council's Subcommittee on Ocean Science and Technology, in consultation with the agencies in the interagency working group, take the following four actions:

- Clearly define the roles and responsibilities of each agency with regard to implementing the *Strategic Plan for Federal Research and Monitoring of Ocean Acidification*.
- Estimate the funding that would be needed to implement the *Strategic Plan for Federal Research and Monitoring of Ocean Acidification*.
- Establish an ocean acidification information exchange.
- Designate the entity responsible for coordinating the next steps in the federal response to ocean acidification.

Agency Comments

We provided a draft of this report for review and comment to the Executive Office of the President; Departments of Agriculture, Commerce, Defense, the Interior, and State; EPA; NASA; and National Science Foundation. None of the agencies commented on our recommendations or findings. NOAA, on behalf of the Department of Commerce, and the Departments of Agriculture and the Interior provided technical comments, which we incorporated, as appropriate.

As agreed with your offices, unless you publicly announce the contents of this report earlier, we plan no further distribution until 30 days from the report date. At that time, we will send copies to the appropriate congressional committees; the Executive Office of the President; the Secretaries of Agriculture, Commerce, Defense, the Interior, and State; the Administrators of EPA, NASA, and NOAA; the Directors of the Bureau of Ocean Energy Management, National Science Foundation, U.S. Fish and Wildlife Service, and U.S. Geological Survey; and other interested parties. In addition, the report will be available at no charge on the GAO website at http://www.gao.gov.

If you or your staff members have any questions about this report, please contact me at (202) 512-3841 or morriss@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff who made key contributions to this report are listed in appendix III.

Steve D. Morris
Acting Director, Natural Resources and Environment

Appendix I: Other Agencies' Actions to Support the Federal Response to Ocean Acidification

In addition to the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation, and the National Aeronautics and Space Administration (NASA), eight other federal agencies are part of the interagency working group on ocean acidification but were not required by the Federal Ocean Acidification Research and Monitoring Act of 2009 (FOARAM) to take specific steps related to ocean acidification.[1] Nonetheless, these agencies have taken a variety of actions to support the federal response to ocean acidification. For example:

- **Bureau of Ocean Energy Management.** The bureau has conducted research and monitoring of ocean acidification conditions in areas of the outer continental shelf where there are ongoing or proposed energy development projects, including in the Arctic Ocean and Gulf of Mexico.[2]
- **Department of State.** The department has contributed funding to help establish an international coordination center for ocean acidification, housed at the International Atomic Energy Agency's environmental laboratories in Monaco. The center is intended to support international monitoring systems and research. The department has also worked to share technical expertise with other countries. For example, it cosponsored a workshop with the government of New Zealand that brought together shellfish experts from both countries to share their experiences with ocean acidification.
- **Environmental Protection Agency (EPA).** EPA has issued final regulations and proposed other regulations under the Clean Air Act to regulate greenhouse gas emissions, including the carbon dioxide

[1]The Department of Energy joined the working group in July 2014, according to the chair of the interagency working group. Because our review was almost complete at that time, this report does not discuss the Department of Energy's activities.

[2]The bureau is responsible for managing the development of oil and gas, renewable, and marine mineral resources along the outer continental shelf of the United States.

emissions that contribute to ocean acidification.[3] EPA has also issued guidance to help states address ocean acidification under the Clean Water Act.[4] In addition, EPA is conducting research in Narragansett Bay, Rhode Island, to better understand the contributions of nutrient pollution to ocean acidification in estuarine and coastal environments.

- **U.S. Department of Agriculture.** The department has funded research related to ocean acidification, including research to better understand the effects of ocean acidification on shellfish aquaculture and how to adapt aquaculture operations to minimize those effects.[5] It also administers agricultural conservation programs that provide billions of dollars in assistance to farmers to reduce nutrient pollution—one of the factors contributing to ocean acidification—and achieve other conservation objectives.[6]
- **U.S. Fish and Wildlife Service.** The service has updated its planning requirements to include ocean acidification as a potential factor to consider in drafting conservation plans and vulnerability analyses for

[3]In 2010, EPA issued final regulations on greenhouse gas emissions from light duty vehicles model years 2012-2016 and from stationary sources, which was partially struck down by the Supreme Court in 2014. *Util. Air Regulatory Group v. Env. Prot. Agency*, 134 S.Ct. 2427 (2014). In 2011, EPA issued final greenhouse gas emissions standards for medium and heavy duty vehicles and, in 2012, final greenhouse gas emissions standards for light duty vehicles model years 2017-2025. In 2012, EPA also proposed performance standards for greenhouse gas emissions from new electric generating units, but the rule was not finalized and was withdrawn in 2014 when EPA proposed three rules on standards for greenhouse gas emissions from stationary sources. *Standards of Performance for Greenhouse Gas Emissions from New Stationary Sources: Electric Generating Utilities*, 79 Fed. Reg. 1430 (Jan. 8, 2014); *Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Generating Units*, 79 Fed. Reg. 34830 (June 18, 2014); *Carbon Pollution Standard for Modified and Reconstructed Stationary Sources: Electric Generating Units*, 79 Fed. Reg. 34960 (June 18, 2014).

[4]*Coral Reef Biological Criteria: Using the Clean Water Act to Protect a National Treasure*, EPA/600/R-10/054 (July 2010); EPA Memorandum on Integrated Reporting and Listing Decisions Related to Ocean Acidification (Nov. 15, 2010).

[5]The department's National Institute of Food and Agriculture chairs the Interagency Working Group on Aquaculture, which works to increase the overall effectiveness and productivity of federal aquaculture research and assistance programs. The working group, previously known as the Joint Subcommittee on Aquaculture, was created by statute and operates under the Office of Science and Technology Policy's National Science and Technology Council.

[6]For more information, see GAO, *Nonpoint Source Water Pollution: Greater Oversight and Additional Data Needed for Key EPA Water Program*, GAO-12-335 (Washington, D.C.: May 31, 2012).

marine and coastal national wildlife refuges.[7] In addition, it is considering establishing coral reefs located in national wildlife refuges, which are often in remote areas and experience little human disturbance, as "sentinel sites" where the service can monitor the effects of ocean acidification.

- **U.S. Geological Survey.** The Geological Survey has researched ocean acidification and its effects by collecting data on ocean chemistry at different locations and studying the effects of acidification on certain species. For example, one of the areas the agency has focused on is the West Florida Shelf in the Gulf of Mexico, where it has studied spatial and temporal variations in carbon chemistry and the effects of ocean acidification on the growth of calcifying organisms. The agency, in conjunction with the U.S. Coast Guard, also monitored ocean chemistry in the Arctic Ocean from 2010 through 2012, documenting that about 20 percent of the area was undersaturated with respect to aragonite, according to an agency official.[8]
- **U.S. Navy.** The Navy has monitored research on ocean acidification conducted by others to assess any potential implications for naval operations. One implication for naval operations described in the research and monitoring plan is the potential for ocean acidification to threaten the food supply in areas of the world that are heavily dependent on marine resources for food, which, in turn, could lead to increased political instability in those regions.[9] The Navy has also helped fund research on the effects that ocean acidification might have on how sound travels through water, because of its potential impact on sonar systems, which are important to naval operations.

[7]The service has management responsibility for many natural resources that may be affected by ocean acidification, including migratory seabirds and some marine mammals, and manages the National Wildlife Refuge System.

[8]Aragonite is a calcium carbonate mineral that many marine organisms use to build shells and skeletons.

[9]Any disruption to food supply that may be caused by ocean acidification will disproportionately affect countries that are dependent on fish protein as a key element of their diet. The Food and Agriculture Organization of the United Nations reported in 2012 that fish accounted for 50 percent or more of animal protein consumed in some island and developing countries, whereas it accounted for only 16.6 percent of animal protein consumed globally.

Appendix II: Approximate Agency Expenditures Related to Ocean Acidification, Fiscal Years 2010 through 2013

The agencies that were part of the interagency working group in 2013 estimated that between fiscal years 2010 and 2013 they collectively spent approximately $88 million on activities directly related to ocean acidification (see table 1). The expenditures shown for fiscal years 2010 and 2011 are estimates provided by the working group's component agencies to the interagency working group.[1] Expenditures shown for fiscal years 2012 and 2013 are preliminary estimates, according to the chair of the interagency working group, and were provided to us by agency officials. For all years, estimates do not include expenditures for actions that may have benefitted the federal response to ocean acidification but that were not made with ocean acidification specifically in mind (e.g., research on the global carbon cycle that provides information useful to ocean acidification researchers but that was funded as part of an agency's climate change portfolio).

Table 1: Approximate Agency Expenditures Directly Related to Ocean Acidification, Fiscal Years 2010 through 2013

Dollars in thousands

Agency	FY 2010	FY 2011	FY 2012[a]	FY 2013[a]
Bureau of Ocean Energy Management	$67	$200	$164	$10
Department of State	0	0	70	0
Environmental Protection Agency	150	385	111	75
National Aeronautics and Space Administration (NASA)	694[b]	365[b]	648	544
National Oceanic and Atmospheric Administration (NOAA)[c]	6,063	7,867	6,464	6,793
National Science Foundation[d]	17,643	7,996	11,749	14, 356
U.S. Department of Agriculture[e]	0	0	0	0
U.S. Fish and Wildlife Service	0	0	0	0
U.S. Geological Survey	1,532	1,498	1,586	1,286
U.S. Navy[f]	0	0	0	0
Total	**$26,149**	**$18,311**	**$20,792**	**$23,064**

Legend: FY = fiscal year.

Source: GAO analysis of agency data. | GAO-14-736

[1]Interagency Working Group on Ocean Acidification, *Second Report on Federally Funded Ocean Acidification Research and Monitoring Activities and Progress on a Strategic Research Plan*.

[a]Expenditures for FY 2012 and FY 2013 are preliminary estimates, according to the chair of the interagency working group.

[b]NASA's expenditures for FY 2010 and FY 2011 differ from those reported by the interagency working group. According to a NASA official, the figures reported here represent expenditures directly related to ocean acidification and do not include expenditures (e.g., for research on the global carbon cycle) that may have benefitted the federal response to acidification but which were not made with it specifically in mind.

[c]NOAA figures include both expenditures by NOAA's ocean acidification program and those by other NOAA programs that were directly related to ocean acidification.

[d]National Science Foundation figures represent funds obligated in a given fiscal year, according to an agency official.

[e]The Department of Agriculture has funded research on ocean acidification issues related to aquaculture. However, the department only joined the interagency working group in 2013 and did not provide to the working group or to us an estimate of its expenditures directly related to ocean acidification for the fiscal years covered here.

[f]The Navy has funded research on the potential effects of ocean acidification on sonar systems but did not provide to the working group or to us an estimate of its expenditures directly related to ocean acidification.

Appendix III: GAO Contact and Staff Acknowledgments

GAO Contact

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Staff Acknowledgments

In addition to the individual named above, Stephen D. Secrist (Assistant Director), Cheryl Arvidson, Christina Cantor, Jonathan Dent, Karen Howard, Timothy M. Persons, Anne Rhodes-Kline, Jeanette Soares, Sarah Veale, and Joshua Wiener made key contributions to this report.

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