The Challenge of Ocean Acidification

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The ocean, our coasts, and the Great Lakes are among the Nation’s most treasured resources. They are an integral part of our national identity and our future. A healthy marine environment feeds our Nation, fuels our economy, supports our cultures, provides and creates jobs, gives mobility to our Armed Forces, enables safe movement of goods, and provides places for recreation.

More than 160 million people live in the coastal watershed counties of the United States, and population in this zone is expected to grow in the future. The oceans help regulate climate and strongly influence weather patterns far into the continental interior. Ocean issues touch all of us in both direct and indirect ways. Oceans also support vibrant economies and coastal communities with numerous businesses and jobs.

In 2010, maritime economic activities such as shipping, marine construction, energy development, commercial fishing, recreational fishing and boating, aquaculture, and tourism contributed $258B in GDP to the national economy and supported 2.8 million jobs. In 2010, 41 percent of our Nation’s GDP ($6 trillion) was generated in the shoreline counties of the United States and territories, including the great Lakes. The value of the ocean to Americas—for commerce, energy, recreation, food, culture, and national security—provides the foundation for our quality of life today, and for future generations.

At the same time, these resources are vulnerable to activities and impacts that diminish their health, productivity, and resilience. Pollution, overfishing, habitat loss, the impacts of climate change, and other factors can increase the vulnerability of coastal and marine resources.

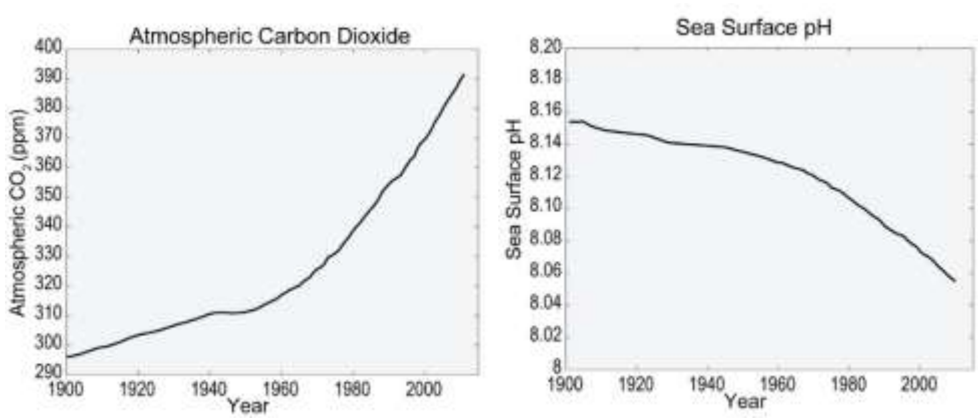
That's why President Obama established the National Policy for the Stewardship of the Ocean, Our Coasts, and the Great Lakes by Executive Order 13547 on July 19, 2010. The National Ocean Policy recognizes our responsibility to improve and maintain the health of the ocean, coasts, and Great Lakes and recognizes the importance of working with States, tribes, and other partners to tackle key challenges through common sense, science-based solutions. Subsequently, in April 2013, the Obama Administration released an implementation plan of concrete actions to carry out the National Ocean Policy and promote a healthy and resilient ocean economy.

This paper discusses the specific challenge of ocean acidification – a key threat to ocean resources which is described in the National Ocean Policy and its Implementation Plan and for which a number of efforts are underway to increase our understanding and develop concrete solutions.

The Problem

Changing climate conditions are already affecting valuable marine ecosystems and the array of resources and services we derive from the sea. One of the most important climate trends, directly related to human-caused emissions of carbon dioxide, is ocean acidification—a trend that is expected to alter marine ecosystems in dramatic ways.

Ocean acidification is caused by the absorption of a portion of excess CO2 in the atmosphere by the ocean's surface layer. Atmospheric CO_2 has risen by about 40 percent above pre-industrial levels. The ocean absorbs about a quarter of human-caused emissions of CO_2 annually, and, over the last 250 years, the oceans have absorbed 560 billion tons of CO_2. When CO_2 dissolves into seawater, some of the CO_2 reacts with water to form carbonic acid (H2CO3). This makes seawater more acidic, as measured on the pH scale.



(Figures 24.2A and 24.2E from *Third National Climate Assessment*, p. 560).

Such changes in ocean chemistry can harm the growth of plants and animals, including recreationally and commercially important fish and shellfish. Marine industries such as shellfish aquaculture, and the jobs and communities they support, face increased impacts from the changing chemistry of our marine waters.

The current observed rate of change in ocean pH is roughly 50 times faster than known historical rates of change. And ocean acidification will continue in the future, as rising atmospheric CO_2 continues to partly dissolve in ocean water. Current projections, based on high-end CO_2 emission scenarios, indicate that average ocean pH could fall as another 0.25 pH units (to pH 7.8) by the end of this century That would correspond to a 2.2-fold increase in hydrogen-ion concentration over the 1990 value.

Scientists estimate that such a large change in ocean pH has not likely been experienced on the planet for the past 100 million years. As indicated below, there is every reason to believe that acidification of this pace and magnitude would severely impact a number of important types of marine life; the extent to which ocean life as a whole could adapt to such changes remains unclear.

Regional Variability

Regional differences in ocean pH can occur as a result of variability in regional or local conditions. For example, ocean upwelling near coasts brings cold, deep ocean waters up to the surface. That water often already has higher levels of CO_2, released by microbes as they break down organic matter that is sinking to the ocean floor. When water with higher background levels of CO_2 absorbs additional CO_2 from the atmosphere, it can cause a spike in the seawater's acidity. As another example, pollution and excess nutrient inputs can cause coastal waters and estuaries to experience enhanced acidification. Finally, polar ocean waters are especially prone to acidification, as discussed in more detail below.

Impacts on the Marine Food Chain

More acidic waters create repercussions along the marine food chain. Calcium carbonate is a skeletal component of a wide variety of organisms in the oceans, including corals. The chemical changes to the balance of carbonate in the oceans, as a result of acidification, make it more difficult for these living things to form and maintain calcium carbonate shells and skeletal components.

(Figure source: Bednaršek et al. 2014.)

This problem is exemplified by pteropods, or “sea butterflies,” which play an important role in the marine food chain, being eaten by a variety of marine species ranging from tiny krill to salmon to whales. The photos to the left show what happens to a pteropod’s shell in seawater that is too acidic. At the top is a healthy shell from a live pteropod from a region where acidity is not too high. The unhealthy shell on the bottom is from a pteropod in a region where the water is more acidic.

The changes brought about by ocean acidification also increase the erosion of coral reefs, resulting in alterations in marine ecosystems that will become more severe as present-day trends in acidification continue or accelerate. Tropical corals are particularly susceptible to the combination of ocean acidification and ocean warming, which would threaten the rich and biologically diverse coral reef habitats.

Effects on Seafood and Aquaculture

More than 90 percent of seafood consumed in the United States is imported, and more than half of this imported seafood comes from aquaculture (fish and shellfish farming). While only one percent of U.S. seafood comes from domestic shellfish farming, the industry is locally important. In addition, shellfish have historically been an important cultural and food resource for indigenous peoples along U.S. coasts. Increased ocean acidification, low-oxygen events, and rising temperatures are already affecting shellfish aquaculture operations. While the effects on aquaculture of rising ocean temperatures may vary in different parts of the globe, acidification will likely reduce growth and survival of shellfish stocks in all regions.

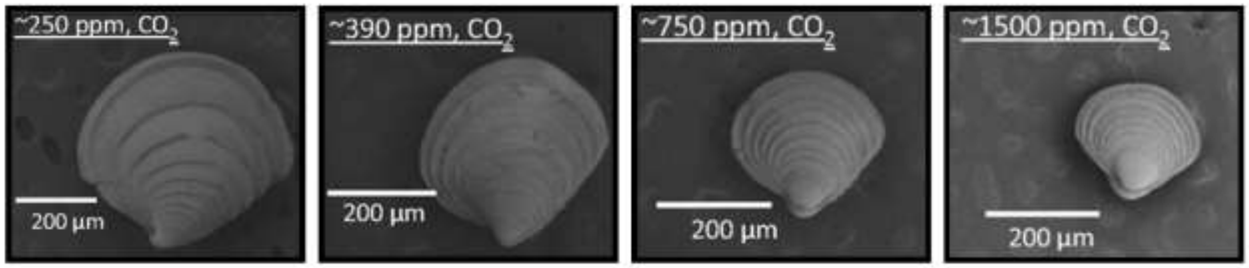


Figure source: *Third National Climate Assessment*, p. 561, from Talmage and Gobler 2010.

A graphic example of how more acidic ocean water can negatively affect the growth of shellfish is depicted in the above photos. Each clam shown is from the same species and is the same age—36 days. They were grown in the laboratory under varying levels of CO_2 in the air. As the photos show, as CO_2 levels rise progressively from left to right, the 36-day-old clams are smaller. The highest atmospheric CO_2 level, about 1500 parts per million (ppm; far right), is higher than most projections for the end of this century but could occur locally in some estuaries.

Overall, economically important species such as oysters, mussels, and sea urchins are highly vulnerable to changes in ocean conditions brought on by climate change and rising atmospheric CO_2 levels. Some important cultured species may be influenced in larval and juvenile developing stages, during fertilization, and as adults, resulting in lower productivity. For example, studies on native Olympia oysters (*Ostrea lurida*) show that there is a "carry-over" effect of acidified water–oysters exposed to acidic conditions while in the juvenile stage continue to grow more slowly in later life stages.

Ocean acidification has already changed the way shellfish farmers on the West Coast of the United States conduct business. For oyster growers, the increasing acidity of ocean water made it more corrosive to young shellfish raised in aquaculture facilities. Growers at Whiskey Creek Hatchery, in Oregon's Netarts Bay, found that low pH seawater during spawning reduced growth in mid-stage larval (juvenile) Pacific oysters. Facilities like the Taylor Shellfish Farms hatchery on Hood Canal in Washington State have changed their production techniques to respond to increasing acidification in Puget Sound.

The impact of the combination of upwelling acidic ocean water, which is a natural variation, and increasing water acidity from rising atmospheric CO_2 illustrates the potential for periodic episodes of enhanced acidity harmful to shell-forming marine life, especially in coastal regions. As a result, there is an increasing need for real-time information about water chemistry conditions, such as data obtained through the use of sensor networks. In the case of Whiskey Creek, instruments installed in collaboration with ocean scientists created an "early warning" system that allows oyster growers to choose the time they take water into the hatchery from the coastal ocean. This capability allows them to avoid the lower-pH water related to upwelling and the commensurate loss of productivity in the hatchery.

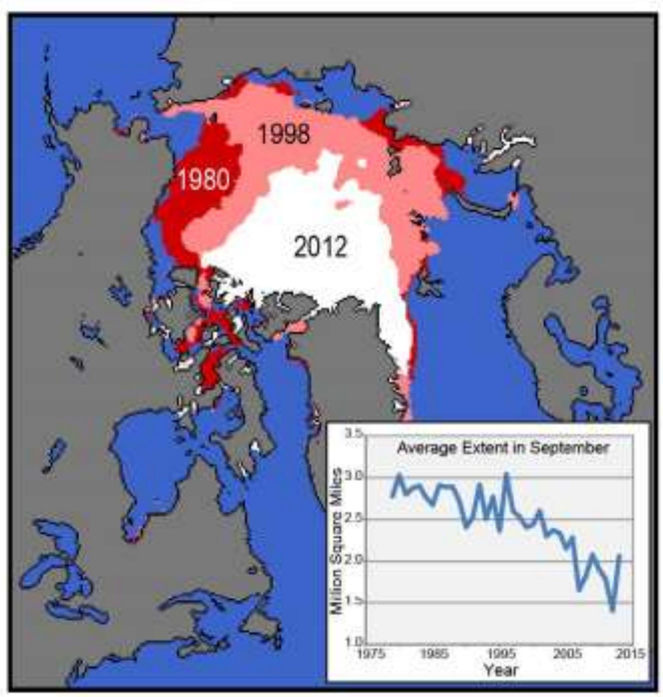
There are also biologically based response strategies for some shellfish. Research on some oyster species such as Pacific oyster (*Crassostrea gigas*), the commercially important species in U.S. West Coast aquaculture, shows that specially selected strains can be more resistant to acidification.

Action groups, such as the California Current Acidification Network (C-CAN), are working to address the needs of the shellfish industry – both wild and aquaculture-based fisheries – in the face of ocean change. These efforts bring scientists from across disciplines together with aquaculturists, fishermen, the oceanographic community, and state and federal decision-makers to ensure a concerted, standardized, and cost-effective approach to gaining new understanding of the impact of acidification on ecosystems and the economy.

Ocean Acidification in Polar Regions

Polar ocean waters are particularly prone to acidification because of colder water temperatures and lower salt content, the latter resulting from freshwater input from melting sea ice and large rivers. These factors allow more carbon dioxide to dissolve into seawater, leading to greater acidification. Acidity reduces the capacity of important plankton species and marine organisms that build shells and other hard parts, which in turn impacts the food available to important fish species.

The decreasing pH of polar surface ocean waters in particular will have strong ecosystem and socioeconomic impacts on the Bering Sea on Alaska's West Coast, which is highly dependent on commercial and subsistence fisheries. Assuming Arctic sea ice shrinkage continues along the trajectory shown in this figure, the vulnerability of Arctic waters will increase.



(Figure source: *Third National Climate Assessment, p. 517, Figure 22.2).*

Periodically through the year, acidification is already reaching a critical threshold for organisms living in Alaska's continental shelves. Certain algae and animals (clams, oysters, and crab) form their shells from carbonate minerals (aragonite and calcite) that dissolve when ocean acidity exceeds that threshold. These organisms form a crucial component of the marine food web that sustains life in waters off Alaska. Shelled pteropods, the tiny planktonic snails whose vulnerability to acidifying conditions was described above, are an especially critical link in high-latitude food webs, since they are near the base of the food chain, and commercially important species such as pink salmon depend heavily on them for food. A 10-percent decrease in the population of pteropods could mean a 20-percent decrease in an adult pink salmon's body weight.

Actionable Science

President Obama's National Ocean Policy highlights the need to improve the resilience of ocean, coastal, and Great Lakes ecosystems, communities, and economies; to use the best available science and knowledge to inform decisions affecting the ocean; and to enhance humanity's capacity to understand, respond, and adapt to a changing global environment.

That's why the Policy's Implementation Plan specifically calls out the need for sustained scientific research, innovative technologies, and high-quality information in order to maintain or restore ocean resources in the face of environmental change and other threats – including by preparing for and responding to the impacts of climate change and ocean acidification.

Among a number of activities underway to carry out this set of actions, in March 2014, the U.S. Government released a new *Strategic Plan for Federal Research and Monitoring of Ocean Acidification.* The Strategic Plan, mandated by the Federal Ocean Acidification Research and Monitoring Act of 2009, articulates a clear vision and specific goals to gain a better understanding of the process of ocean acidification, its effects on marine ecosystems, and the steps that must be taken to prevent harm from ocean acidification.

Key to the achievement of this vision is research to understand how marine organisms respond to ocean acidification and how their physiological responses interact with other stressors in the ocean environment. Ocean acidification appears to have wide-ranging effects on how organisms function, including hitherto unanticipated effects on their nutrition, behavior, and reproductive capabilities. The effects of ocean acidification on specific organisms can also alter ocean ecosystems in important ways. Yet, while these direct effects are important, ocean acidification is not happening in isolation, and understanding the potential synergistic interactions of ocean acidification with other stressors is essential. New measurement approaches and technologies, combined with the development of best practices for carrying out those measurements, are part of the Strategic Plan's vision to understand all of the major variables that affect an organism's response to ocean acidification, as well as how those responses propagate up through ecosystems.

The Strategic Plan calls for research, from the organism level to the ecosystem level, to be coupled with the implementation of a comprehensive global and regional ocean acidification observing system. This system would include monitoring of both physical and biological effects, in both the open ocean and at coastal and estuarine sites. Effective management and integration of data collected through this observing system, so that the data can be shared and integrated across disciplinary and organizational boundaries, is an essential part of the Plan. For example, understanding how an organism's responses relate to trends seen through monitoring can help in the development of real-time early warning systems of damage from ocean acidification.

The Plan also calls for the development of new and enhanced models to understand how ocean acidification will change the ocean carbon cycle and affect marine ecosystems and organisms. This is essential for analyzing potential adaptation and mitigation strategies. Developing successful mitigation, adaptation, and conservation strategies will also require an assessment of the socioeconomic and cultural impacts of ocean acidification on coastal and marine environments. And the Strategic Plan also calls for education, outreach, and engagement—both to foster public understanding of ocean acidification and to ensure that stakeholders are involved adequately in planning for research, mitigation, and adaptation activities.

In addition, in May of 2014, the Obama Administration released the third U.S. National Climate Assessment—the most comprehensive scientific assessment ever generated of climate change and its impacts across every region of America and major sectors of the U.S. economy. Developed over four years by hundreds of the Nation's top climate scientists and technical experts—and informed by thousands of inputs from the public and outside organizations gathered through town hall meetings, public-comment opportunities, and technical workshops across the country, the third National Climate Assessment represents the most authoritative and comprehensive knowledge base about how climate change is affecting America now and what's likely to come over the next century. The NCA contains an entire section devoted to the science of ocean acidification, providing essential information about the mechanisms of ocean acidification, observed impacts, and projections for the future.

The following additional actions are underway in agencies across the Federal Government to increase understanding of the problem and potential solutions to ocean acidification:

- NOAA developed and supports four experimental facilities to study the response of species to ocean acidification. Research at these facilities targets a range of finfish, zooplankton, and phytoplankton species, all of which are economically or ecologically important. NSF provided over $50 million in support to basic research on ocean acidification, including funds to develop the laboratories needed to conduct species response studies. NASA has supported six projects that use satellite remote sensing observations, as well as *in situ* observations and models, to support the FOARAM Act's objectives and NASA's mission.

- NOAA, NSF, NSA, EPA, BOEM, and USGS have supported studies that address monitoring ocean chemistry and biological impacts associated with ocean acidification. NOAA ocean acidification monitoring focuses on North American coastlines (Atlantic, Gulf of Mexico, Pacific, and Alaska) and open oceans and tracks the extent and rate of change of acidification in US coastal and open-ocean waters, and provides context for understanding ecosystem responses to ocean acidification and the data for model validation.

- The US Government deploys a variety of assets for monitoring, including fixed-site observing platforms (e.g., moorings and piers), ships of opportunity, dedicated hydrographic cruises, remote sensing, wave gliders, and profiling floats. A key aspect of improving ocean-acidification monitoring capacity is advanced technology development. Efforts have been engaged to developed new and improved ocean- acidification sensors for use in both sustained monitoring and in industry applications.

- NOAA supports a number of regional modeling exercises on ocean carbon chemistry in the Greater Caribbean and the California Current. NOAA also models how ocean acidification may affect coastal and marine ecosystems and living marine resources in the North Pacific and North Atlantic. Many of the projects funded by NSF and NASA also support modeling work on ocean biogeochemistry and the response of species and ecosystems to ocean acidification.

- Federal agencies are working to understand how ocean acidification will impact human communities and the economy. NOAA's socio-economic work focuses on the impacts of ocean acidification on fisheries and fishery-based economies and includes development of strategies for managing living marine resources under ocean acidification. EPA has developed models to project the economic impact of ocean acidification on coral reefs.

- All Federal agencies involved in ocean acidification research have made a strong commitment to education, outreach, and engagement on the topic. Highlights of these activities include federal participation in state and regional action on ocean acidification, including the Washington State Blue Ribbon Panel on Ocean Acidification, the West Coast Ocean Acidification and Hypoxia Panel, and the Northeast Coastal Acidification Network; the education and professional training of scores of K-12, undergraduate, and graduate students; and collaborative work with experiential learning facilities, like aquaria and science centers, to develop interactive exhibits on ocean acidification and its impacts.

The Need for International Partnership

Ocean acidification is a global phenomenon. Addressing this complex challenge will require all-hands-on deck and sustained collaboration around the world. International coordination and cooperation are essential to this task.

The broad themes of the U.S. Strategic Plan outlined above require cooperation, support, and integration with a larger international context. Developing and implementing international engagement strategies and facilitating partnerships is a key part of the U.S. Strategic Plan. For example, the United States is participating in the work of the International Atomic Energy Agency Ocean Acidification International Coordination Centre. The International Coordination Centre will seek to facilitate, promote, and communicate about global actions on ocean acidification, and the United States will be represented on its Ocean Acidification Advisory Board.

Notes

The scientific information in this report in the sections on "The Problem," "Regional Variability," "Impacts on the Marine Food Chain," "Effects on Seafood and Aquaculture," and Ocean Acidification in Polar Regions" is derived from chapter 24, "Oceans and Marine Resources," and chapter 22, "Alaska," of *Climate Change Impacts in the United States: The Third National Climate Assessment*, which was adopted and published by the U.S. government in May 2014. The Office of Science and Technology Policy gratefully acknowledges the work of the following individuals who authored these chapters. For chapter 22, they are the Convening Lead Authors—F. Stuart Chapin III, University of Alaska Fairbanks, and Sarah F. Trainor, University of Alaska Fairbanks—and the Lead Authors—Patricia Cochran, Alaska Native Science Commission, Henry Huntington, Huntington Consulting, Carl Markon, U.S. Geological Survey, Molly McCammon, Alaska Ocean Observing System, A. David McGuire, U.S. Geological Survey and University of Alaska Fairbanks, and Mark Serreze, University of Colorado. For chapter 24, they are the Convening Lead Authors—Scott Doney, Woods Hole Oceanographic Institution, and Andrew A. Rosenberg, Union of Concerned Scientists—and the Lead Authors—Michael Alexander, National Oceanic and Atmospheric Administration, Francisco Chavez, Monterey Bay Aquarium Research Institute, C. Drew Harvell, Cornell University, Gretchen Hofmann, University of California Santa Barbara, Michael Orbach, Duke University, and Mary Ruckelshaus, Natural Capital Project.

The full chapters of the *Third National Climate Assessment* can be found on the web at:
http://nca2014.globalchange.gov/report/regions/oceans and
http://nca2014.globalchange.gov/report/regions/alaska

Cover and Page 5:

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