FOURTH REPORT ON FEDERALLY FUNDED OCEAN ACIDIFICATION RESEARCH AND MONITORING ACTIVITIES

PRODUCT OF THE

National Science and Technology Council

December 2016

EXECUTIVE OFFICE OF THE PRESIDENT

NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

WASHINGTON, D.C. 20502

December 20, 2016

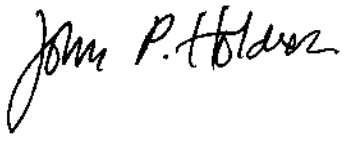
Dear Colleagues:

I am pleased to transmit to you the *Fourth Report on Federally Funded Ocean Acidification Research and Monitoring Activities*, a biennial report to Congress for Fiscal Years 2014 and 2015 that responds to the Federal Ocean Acidification Research and Monitoring Act of 2009 (P.L 111-11, Subtitle D). This report was produced by the Interagency Working Group on Ocean Acidification, organized under the National Science and Technology Council; Committee on Environment, Natural Resources, and Sustainability; Subcommittee on Ocean Science and Technology.

The report summarizes Federally-funded ocean acidification research and monitoring activities, provides expenditures for these activities, and details how Federal agencies are implementing the 2014 *Strategic Plan for Federal Research and Monitoring of Ocean Acidification* in a coordinated and complementary manner. Unlike previous biennial reports on ocean acidification research and monitoring activities, this document is organized by geographic region so stakeholders can more easily find activities in their region of interest.

The Obama Administration is deeply concerned about ocean acidification and committed to better understanding and addressing its impacts on America's communities, economy, and environment. Many members of Congress share this concern and commitment and have supported Federal activities on ocean acidification.

Sincerely,



John P. Holdren
Assistant to the President for Science and Technology
Director, Office of Science and Technology Policy

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The Office of Science and Technology Policy (OSTP) was established by the National Science and Technology Policy, Organization, and Priorities Act of 1976. OSTP's responsibilities include advising the President in policy formulation and budget development on questions in which science and technology are important elements; articulating the President's science and technology policy and programs; and fostering strong partnerships among Federal, tribal, state, and local governments, and the scientific communities in industry and academia. The Director of OSTP also serves as Assistant to the President for Science and Technology and manages the NSTC. More information is available at www.WhiteHouse.gov/ostp.

About the Subcommittee on Ocean Science and Technology

The purpose of the Subcommittee on Ocean Science and Technology (SOST) is to advise and assist on national issues of ocean science and technology. The SOST contributes to the goals for Federal ocean science and technology, including developing coordinated interagency strategies, and fosters national ocean science and technology priorities, including implementation of the National Ocean Policy.

About the Interagency Working Group on Ocean Acidification

The Interagency Working Group on Ocean Acidification (IWG-OA) advises and assists the SOST on matters related to ocean acidification, including coordination of Federal activities on ocean acidification and other interagency activities as outlined in the Federal Ocean Acidification Research And Monitoring Act of 2009 (P.L. 111-11, Subtitle D).

About this Document

This document was developed by the IWG-OA. The document was published by OSTP.

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Executive Summary

The ocean provides vital resources and services for sustaining humankind including food, recreation, transportation, energy, nutrient-cycling, and climate moderation. Through such resources and services, the ocean substantially contributes to the United States economy. Science is only beginning to indicate how changes in seawater chemistry due to ocean acidification may affect marine organisms and ecosystems and the resources and services they provide. But based on studies to date of acidification's observed and projected impacts on a number of important classes of marine organisms, significant changes in marine ecosystems appear to be likely.

This document is the fourth biennial summary and progress report submitted under the Federal Ocean Acidification Research and Monitoring Act of 2009 (FOARAM Act, P.L. 111-11, Subtitle D). The FOARAM Act specifies that the Subcommittee on Ocean Science and Technology (SOST) under the National Science and Technology Council Committee on Environment, Natural Resources, and Sustainability shall transmit a biennial report to the Committee on Commerce, Science, and Transportation of the Senate and the Committee on Science, Space, and Technology and the Committee on Natural Resources of the House of Representatives that includes:

1. A summary of Federally-funded ocean acidification research and monitoring activities, including the budget for each of these activities; and
2. An analysis of the progress made toward achieving the goals and priorities for the interagency research plan developed by the Subcommittee under section 12405 of the FORARAM Act.

The SOST's Interagency Working Group on Ocean Acidification produced this report, which summarizes Federal agency activities related to ocean acidification for fiscal years (FY) 2014 and 2015. The report is organized into sections covering geographic regions. Within each region, information is organized by the thematic areas as outlined within the *Strategic Plan for Federal Research and Monitoring of Ocean Acidification (Strategic Plan)*, and then by Federal agency. Some regions did not host activities for every thematic area, and an additional category called "Other ocean acidification research and monitoring activities" is used for items not adequately captured by the *Strategic Plan's* themes.

The Appendix provides a summary of expenditure amounts for individual agencies' ocean acidification research and monitoring activities. In the expenditures tables, activities are classified as either having a primary focus on ocean acidification or being contributing activities that were designed for other purposes but clearly provide information useful for understanding ocean acidification. In FY 2014, Federal agencies provided approximately $27 million (M) toward activities with a primary focus on ocean acidification and an additional $9M for contributing activities. In FY 2015, Federal funding was approximately $18M for primary activities and $9M for contributing activities. The funding decrease from FY 2014 to FY 2015 reflects the National Science Foundation's front-funding approach to multi-year projects rather than a significant long-term reduction in ocean acidification investments. Primary and contributing activities included monitoring of ocean chemistry and biological impacts, research to understand species-specific and ecosystem responses to ocean acidification, biogeochemical and ecosystem modeling, technology development, assessment of socioeconomic impacts from ocean acidification, education and outreach activities, data management and integration, and other activities.

Introduction

Ocean acidification (OA) refers to a reduction in the pH of the ocean over an extended period, typically decades or longer, which is primarily caused by the uptake of carbon dioxide (CO_2) by the ocean from the atmosphere. It can also be caused by other chemical additions to or subtractions from the ocean. The long-term consequences of ocean acidification are still being determined, but likely include serious impacts on marine ecosystems and the resources and services those systems provide to society and the United States economy.

Some organisms appear to be particularly sensitive, while others are not. OA can negatively impact many organisms that make shells or skeletons from calcium carbonate (e.g., corals, marine plankton, shellfish), making it harder for them to build and maintain these structures. Changes in CO_2 and pH can impact other physiological processes as well, affecting species growth, survival, fertilization, embryonic/larval development, and behavior. There likely will be ecological "winners" and "losers" as a result of ocean acidification, causing shifts in the structure and composition of marine food webs and ecosystems.

While understanding of how OA affects the range of species driving economic activity is growing, it is clear that the impacts of OA on marine industry could extend far into and beyond local and regional economies. OA also has important cultural implications. To many coastal communities, OA is a natural resource issue and a significant challenge to continued cultural identity. Many fishers and shellfish farmers depend on shellfish to support their families. Tribal communities also harvest wild and cultured shellfish for ceremonial and subsistence purposes.

The Federal Ocean Acidification Research and Monitoring Act of 2009 (FOARAM Act, Public Law 111-11, Subtitle D) directed the Subcommittee on Ocean Science and Technology (SOST) under the National Science and Technology Council Committee on Environment, Natural Resources, and Sustainability to create an Interagency Working Group on Ocean Acidification (IWG-OA). Section 12404(c) of the FOARAM Act further specifies that the SOST will transmit a biennial report, prepared by the IWG-OA, to the Committee on Commerce, Science, and Transportation of the Senate and the Committee on Science, Space, and Technology and the Committee on Natural Resources of the House of Representatives that includes:

1. A summary of Federally-funded ocean acidification research and monitoring activities, including the budget for each of these activities; and
2. An analysis of the progress made toward achieving the goals and priorities for the interagency research plan developed by the IWG-OA under section 12405 of the FOARAM Act.

This document constitutes the fourth biennial summary and progress report of the SOST's IWG-OA and covers Fiscal Years (FY) 2014 and 2015. The SOST initially chartered the IWG-OA in October 2009. The National Oceanic and Atmospheric Administration (NOAA) chairs the IWG-OA, and representatives include the National Aeronautics and Space Administration (NASA), National Science Foundation (NSF), United States Geological Survey (USGS), Environmental Protection Agency (EPA), Bureau of Ocean Energy Management (BOEM), Department of State (DOS), United States Navy, United States Fish and Wildlife Service (FWS), and United States Department of Agriculture (USDA). In FY 2015, the IWG-OA added a representative from the National Park Service (NPS), and in FY 2016, the group added a representative from the Smithsonian Institution (SI). This report includes SI's OA activities and expenditures in FY 2014

and FY 2015. The group meets regularly to coordinate OA activities across the Federal government and has made significant progress toward meeting the goals of the FOARAM Act. This report includes the Department of the Interior's Bureau of Indian Affairs (BIA) OA-related activities, though BIA is not a member of the IWG-OA.

This report is organized into sections corresponding to the nine geographic regions in which Federal agencies studied OA in FY 2014 and FY 2015, as well as one section devoted to national efforts and one section describing global efforts. The content within the sections covering geographic regions is organized by the thematic areas as outlined within the *Strategic Plan for Federal Research and Monitoring of Ocean Acidification (Strategic Plan),* and then by Federal agency. Some regions did not host activities for every thematic area. An additional category called "Other ocean acidification research and monitoring activities" is used for efforts not adequately captured by the thematic areas. The Appendix provides a summary of expenditure amounts for individual agencies' ocean acidification research and monitoring activities. In the Appendix, activities are classified as having either a primary focus on ocean acidification or being contributing activities that were designed for other purposes but clearly provide information useful for understanding ocean acidification.

Global

Ocean acidification is a global phenomenon. Few research projects, however, are truly global in nature. Typically, research focuses on local and regional levels and builds information that can give insight into global-level processes and phenomena, often through synthesis projects. Thus, only a portion of the portfolio of Federal activities is considered "global" even though the entire portfolio builds knowledge useful for global application.

During FY 2014 and 2015, Federal global-scale research focused on understanding historical ocean chemistry conditions, using satellite and autonomous observations to monitor and characterize ocean chemistry and ecosystems, projecting future ocean and marine ecosystem conditions, and developing and maintaining the data systems needed to preserve data collected by ocean acidification-focused projects. Global-scale research placed an emphasis on open ocean environments and coral reefs ecosystems, and included development of the technology needed to monitor these areas. These projects yielded insight into how ocean acidification may influence large marine ecosystems. In addition, over the past two years, the Federal government, led by the State Department, interacted with other nations to consider and address this important phenomenon.

Theme 1. Research to understand implications of ocean acidification

NSF

NSF funded projects that focused on reconstructing and understanding variability in ocean pH over timescales longer than the instrumental record (i.e., centuries to millions of years), plus projects aimed at developing the geochemical tools ("proxies") required for such reconstructions. Projects particularly address changes in the marine carbon cycle over periods of abrupt climate change and climate transition, such as the Paleocene-Eocene Thermal Maximum and the mid-Pleistocene Transition. These studies consider a variety of calcifying organisms, both plankton (e.g., coccolithophores) and benthic (e.g., surface corals and calcifying algae). Additionally, NSF provided support for a postdoctoral researcher conducting

experimental work on three species of pico-eukaryotic plankton from an oligotrophic ocean region to determine how they respond to OA and nutrient conditions. NSF also provided funding to finalize studies on the ability of phytoplankton to evolve in response to increasing levels of CO_2.

NASA

NASA continued funding satellite research that investigates Earth system science, including ocean color remote sensing. Ocean color can be used to measure particulate inorganic carbon, biogenic silica, and partial pressure of CO_2 (pCO_2), which are properties of the ocean linked to ocean chemistry and ecology. NASA also funded efforts to reduce uncertainty when measuring phytoplankton chlorophyll and many other ocean biology, ecology, and biogeochemistry variables in the ocean. These efforts provide the foundation to observe algal physiological processes, such as photosynthesis, evaluate phytoplankton health, and provide global datasets for modeling efforts that include ocean acidification. Much of this work is also in support of NASA's Earth Science Carbon Cycle Science program.

USGS

USGS supported studies that identify and characterize natural refuges for coral reef species from ocean acidification. USGS also supported regional-scale assessments of erosion rates in coral reef ecosystems of the Atlantic Ocean, Pacific Ocean, and Caribbean Sea, and integrated process studies to identify and quantify multi-stressor factors contributing to reef ecosystem degradation. These efforts set baselines for the current state of the physical environment of coral reefs, and provide data sets and process rates for modeling future ocean acidification impacts.

Theme 2. Monitoring of ocean chemistry and biological impacts

NOAA

NOAA operated open-ocean OA moorings in the Bay of Bengal, in the Arctic Ocean north of Iceland, off the west coast of Chile, and off the island of Chuuk in the South Pacific. International partners co-funded all of these moorings. NOAA also operated a number of other moorings that partially address OA by collecting data on CO_2, but no other carbon-chemistry parameter. NOAA and NSF together supported the collection of the open-ocean carbon data that provide the basis for understanding how the global ocean is changing in response to rising levels of atmospheric CO_2 (see NSF's support of the Climate and Ocean Variability, Predictability, and Change (CLIVAR) program below) Monitoring was done as part of the international Global Ocean Ship-based Hydrographic Investigation Program and Ship of Opportunity – CO_2 Programs with global data synthesized in the Surface Ocean CO_2 Atlas. These data are used to provide a global picture of the seasonal to decadal changes in carbon system parameters due to atmospheric CO_2 uptake by the ocean and resulting ocean acidification. A number of programs inside NOAA contributed to global monitoring efforts, including the Climate Program Office (Ocean Observing and Monitoring Division), Ocean Acidification Program, Pacific Marine Environmental Laboratory, and Atlantic Oceanographic and Meteorological Laboratory.

NOAA provided expert assessments and review of OA in the context of multiple stressors under climate and biogeochemical change for the scientific community at large, and as lead chapter reviewer as part of the United States Government review of the United Nations World Ocean Assessment. NOAA has also

been instrumental in the establishment and growth of the Global Ocean Acidification Observing Network, with the NOAA OA Program Director serving as co-chair of the network.

NSF

NSF provided for ongoing continuous plankton recorder surveys in the North Atlantic Ocean in FY 2014 and 2015. NSF also supported mid-ocean time series stations in both the Atlantic and Pacific Oceans. In the Atlantic Ocean, NSF continued to support observations at the Bermuda Atlantic Time-Series that include measurements of ocean primary productivity and changes in the ocean biota, nutrients, pH, and carbonate chemistry. In the Pacific Ocean, NSF continued to support comparable observations at the Hawaii Ocean Time-Series. These ocean time-series sites now provide more than a 25-year record of mid-ocean environmental conditions. The University-National Oceanographic Laboratory System vessels provided significant ship support for site sampling. These contributions are not included in the Appendix. NSF also supported CO_2 measurements as part of the United States CLIVAR repeat hydrography survey program (see NOAA section above). The NSF Ocean Observatories Initiative (OOI) is now providing global ocean buoy observations at four sites: Global Station Papa in the North Pacific Ocean; Global Southern Ocean; Global Irminger Sea in the North Atlantic Ocean; and Global Argentine Basin in the South Atlantic Ocean. OOI assets will provide considerable data that will contribute to an increased understanding of OA.[1]

NASA

NASA continued to support the Pre-Aerosol, Cloud, and ocean Ecosystem (PACE) satellite mission, which continued pre-formulation activities in FY 2014 and FY 2015. This mission has a science focus on: (1) understanding and quantifying global aerosol and cloud dynamics, aerosol-ocean interactions, ocean biogeochemical cycling, and ecosystem function due to natural and anthropogenic forcings from environmental/climate variability and change; (2) extending key Earth system data records on global ocean ecology, ocean biogeochemistry, clouds, and aerosols; (3) understanding and resolving/quantifying the role of aerosols and clouds in physical climate; and (4) enabling carbon monitoring and management, contributing to better weather forecasting, and delineating the impacts of weather events on coastal ecosystems to enable resource management. NASA plans for PACE to move in to formulation in FY 2016.

In FY 2015, NASA funded a field project focused on coral reefs. The COral Reef Airborne Laboratory (CORAL) investigation is designed to determine the functional link between coral reef condition and the biogeophysical (i.e., biological and environmental) forcings that impact coral reef ecosystems. Coral reefs are among the first natural ecosystems to respond critically, dramatically, and globally to both local environmental degradation and global climate change, including an acidifying ocean. An estimated 25 to 30 percent of reefs worldwide have already been severely degraded (International Society for Reef Studies Consensus Statement, 2015), 15 percent are critically threatened with loss in the next 10 to 20 years, and another 20 percent are under threat of loss in the next 20 to 40 years (Wilkinson, 2008). On closer inspection, the data supporting these predictions are surprisingly sparse, because virtually all reef

[1] None of the construction costs or operations and maintenance support for any of the OOI facilities are included in this report.

assessments rely on in-water survey techniques that are laborious, expensive, and limited in spatial scope. Further, there are no existing models that quantitatively relate reef condition to a full suite of biogeophysical forcing parameters.

Remote sensing is the only available tool for acquiring uniform data on reef condition at regional to global scales. CORAL has begun to provide the data necessary to develop ecosystem-scale models linking reef condition to biogeophysical forcings. The investigation will map one to three orders of magnitude more of the world's coral reefs than is currently done. With models based on these data, scientists, resource managers, and policy makers will be able to better understand how natural and anthropogenic processes have an impact on reefs, and thus make more informed decisions toward their conservation. Over the next decade, as airborne measurements give way to satellite observations, the focus can shift from model development to near-real-time reef condition assessment and ecosystem forecasting.

SI

To address issues of spatial and temporal variability of acidification in coastal ecosystems, the Smithsonian Institution incorporated pCO_2 measurements at several of its marine-science directorates and is in the process of incorporating total alkalinity measurements. These efforts are designed to amass standardized spatiotemporal data that characterize carbonate-chemistry dynamics at local and regional scales that can be compared to similar data across larger geographic scales (e.g., latitudinal gradients and inter-ocean coastal ecosystems). These monitoring efforts are part of a larger Smithsonian coastal ocean observing initiative, the Marine Global Earth Observatory, directed by the Tennenbaum Marine Observatories Network. By specializing in coastal ecosystems – where marine biodiversity and people are concentrated and interact most – this initiative is designed to provide policymakers with science to support innovative solutions and advance management and protection of the ocean. Currently, measurements are being taken at three core Tennenbaum Marine Observatories Network sites: SI Tropical Research Station (Caribbean), Bocas del Toro, Panama; SI Marine Station (Indian River Lagoon), Fort Pierce, Florida; and SI Environmental Research Center (Chesapeake Bay), Edgewater, Maryland. These data are elements of a larger, long-term Marine Global Earth Observatory environmental/ecological data aimed at tracking and understanding anthropogenic impacts at multiple spatial and temporal scales.

Theme 3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms

NOAA

NOAA, through its Geophysical Fluid Dynamics Laboratory (GFDL), contributes to OA research focused on three areas: (1) sensitivity studies and analysis of historical and projected OA in coupled climate carbon Earth System Models (ESM2M using GFDL's Modular Ocean Model version 4.1 and ESM2G using the Generalized Ocean Layer Dynamics code base); (2) prototyping of a global eddying (10 kilometer resolution) climate model with OA; and (3) application of these models to assess multiple stressors, including OA, on ocean ecosystems and biogeochemistry. These efforts are highly collaborative, leveraging work both nationally and internationally, and include both public scientific contributions and ongoing model development and preparation for future contributions.

NOAA Earth System Model experiments over the FY 2014–2015 period included assessment of: (1) coupled carbon-climate trajectories and feedbacks under idealized linear CO_2 emission scenarios; and (2) acidification and ecosystem responses under reserved concentration CO_2 emission scenarios. NOAA's California Cooperative Oceanic Fisheries Investigations report highlighted the high-resolution prototyping simulations applied to the California Current. NOAA's public Earth System Model contributions in coupled carbon-climate and associated OA have been highlighted as part of several impacts studies, including the role of Southern Ocean CO_2 uptake and feedbacks, global biogeochemical feedbacks on acidification, the potential for extreme sensitivity of deep North Atlantic Ocean ecosystems to acidification impacts, and the potential for coral reef systems to respond to warming.

NSF

In 2014, NSF supported a modeling effort to improve estimates of carbonate saturation distributions by adding particle aggregation and sinking to a global ocean biogeochemical model.

Theme 4. Technology development and standardization of carbonate chemistry measurements on moorings and autonomous floats

NOAA

NOAA continued to focus on developing and deploying observing gliders in FY 2014 and FY 2015. Wave gliders combine wave-powered, autonomous surface vehicles with instruments to take pCO_2 (air and water), pH, temperature, and salinity measurements. NOAA refined the technology used in wave gliders and deployed gliders to assess the temporal variability of upwelling and hypoxia between research cruises on the United States West Coast. These data have been applied with algorithms to predict pH and aragonite saturation, and have assisted in identifying sites for future mooring deployments. NOAA also used a wave glider and a Slocum glider to assess the influence of glacial melt on carbon chemistry in surface and subsurface waters of Prince William Sound, Alaska. NOAA tested the utility of saildrones, a wind driven sensor package that can collect data on surface water chemistry, in the Arctic, Gulf of Mexico, and equatorial Pacific Ocean, as this technology could be highly useful in OA observing. Finally, NOAA worked to develop a carbon "prawler," a wave-energy driven sensor package that can collect data through the water column by traveling up and down a mooring cable.

Given the limitations inherent in using pH and pCO_2 to constrain the carbonate system and limitations on using current technology at depth, it is critically important to develop additional, robust sensors for measuring dissolved inorganic carbon, pH, and pCO_2 in surface and sub-surface waters. NOAA invested in development and testing of next-generation technology for measuring dissolved inorganic carbon using spectrophotometry and infrared sensors. NOAA's Pacific Marine Environmental Laboratory also served as the Validation Team for the Wendy Schmidt Ocean Health X Prize competition focused on developing pH sensors that are affordable and accurate at the surface and at depth. As the Validation Team, the Pacific Marine Environmental Laboratory made the official measurements by which all of the competition teams' measurements were judged, and was involved in all three testing phases of the contest.

NSF

NSF continued to support the production of CO_2 reference standards to foster national OA research efforts. Funding allocated in FY 2013 covered the production and distribution of reference standards for

3 years. In FY 2014 and FY 2015, NSF invested in new instrumentation to measure pH and other chemical parameters associated with OA.

USGS

USGS, cooperating with NOAA and a number of universities, supported the refinement and standardization of methods for measuring carbon parameters and calcification in coral reef systems. These methods will help build understanding of the metabolic function of reef systems. USGS also supported the development, testing, and improvement of flow-through systems for the rapid measurement of carbonate parameters in water. These systems can operate in both marine and freshwater conditions. With partial funding from NASA, USGS used its mesocosm technology with gliders and drones to calibrate ocean condition data.

USGS is also collaborating with academia on developing an inexpensive pH sensor with precision of 0.01 pH units that can be used in coastal, riverine, and estuarine systems. The device, which incorporates pH, temperature, and salinity sensors, uses Bluetooth technology to connect to a smart phone for use in the field. One of the goals of developing this device is to make taking measurements straightforward for citizen science efforts. USGS has also developed an inexpensive pCO_2 sensor submersible to 1 meter with a working range from 0 to 25,000 parts per million (ppm) pCO_2 and an accuracy of 25 ppm at 400 ppm pCO_2.

Theme 5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems

EPA

Managers, conservationists, and biologists use EPA's Coral Mortality and Bleaching Output model to predict the effects of climate change and OA on coral reefs at local-to-regional scales. Model output has resulted in the application of new economic valuation approaches to estimate damages to coral reefs.

Theme 6. Education, outreach, and engagement strategy on ocean acidification

Multi-agency

In June 2015, a special issue of the journal *Oceanography* highlighting OA was released. This issue focused on information shared at the 2013 OA Principal Investigators' Meeting the United States Ocean Carbon and Biogeochemistry Program organized with supported from NSF, NOAA, and NASA. The issue contains papers assessing the state of OA research in the context of four transitions: (1) single stressor to multiple stressor research; (2) scaling understanding from the short-term (i.e., days, weeks, months) to the long-term (i.e., years, decades); (3) scaling understanding from single species to ecosystems; and (4) moving from disciplinary to transdisciplinary approaches to include the human perspective and explore mitigation and human adaptation options.

NOAA

NOAA guest-edited a special issue of the online magazine Earthzine focused on ocean acidification. *Earthzine*, a publication of the Institute of Electrical and Electronics Engineers' Oceanic Engineering Society and the Group on Earth Observations, has a large, international distribution.

NSF

NSF continues to support international carbon cycling planning and coordinating activities through the Scientific Committee on Oceanic Research.

USGS

USGS is leading the effort by the Ocean Acidification International Coordination Centre to organize international workshops on ocean acidification. These workshops focus on presenting best science practices and setting up national/international networking opportunities for scientists in developing countries. In FY 2014 and FY 2015, workshops took place in Chile, Italy, China, and South Africa. Scientists from over 34 developing countries have participated to date. Follow-on activities to enhance networking capabilities have also been implemented.

DOS

The Our Ocean conference, a Department of State initiative, has become an effective mechanism to identify commitments for significant and meaningful actions to protect the ocean and has complemented other international efforts addressing threats to the ocean. Held in Washington, D.C., in 2014 and in Valparaiso, Chile, in 2015, the first two Our Ocean conferences focused on current key ocean issues: marine protected areas; sustainable fisheries; marine pollution; and ocean acidification. At the 2014 and 2015 conferences, the United States announced contributions of $640,000 and $370,000, respectively, through the International Atomic Energy Agency's Peaceful Uses Initiative to support the Ocean Acidification International Coordination Center located at the Environment Laboratories in Monaco. These contributions, which consist of funding from FY 2014 and 2015, brought the United States contributions to the Ocean Acidification International Coordination Center to a total of $1.3 M since 2012.

At the 2015 conference, the United States also announced FY 2015 funding for the OceAn pH Research Integration and Collaboration in Africa program, known as ApHRICA. This public-private partnership of government, civil society, and private stakeholders aims to increase worldwide coverage of the Global Ocean Acidification Observing Network and expand the ability of coastal states to monitor ocean acidification. With this funding, 13 participants from four African states were trained at a July 2016 workshop in Mauritius in how to deploy, operate, and maintain OA sensors and collect other relevant data for assessing local OA conditions. As a follow up to the workshop, OA monitoring equipment will be delivered to participants to enable the newly trained scientists to collect OA data and fill the critical data gap in that region. Participants will also receive ongoing mentorship from experienced OA scientists from developed countries. This effort also includes making available an online library of training materials and an e-teaching module for data collection, laboratory techniques, and data upload.

Thanks in part to the Our Ocean conferences, OA has become an integral part of the training that United States Foreign Service officers receive at the Foreign Service Institute in preparation to serve as Environment, Science, Technology, and Health officers abroad. The training provides officers with a broad understanding of the science behind OA and the work of other United States agencies on this topic, helping officers become more effective science diplomats.

Partnering with New Zealand, the Department of State funded an OA workshop during the Third International Conference on Small Island Developing States held in September 2014 in Apia, Samoa. The workshop for marine scientists and marine resource managers from the Caribbean, Pacific, and Indian

Ocean regions sought to increase understanding of OA in Small Island Developing States, promote awareness of the need for increased monitoring of OA (including the ecological, biodiversity, and fisheries impacts), and to immerse Small Island Developing States into existing global OA observing efforts. The participants stressed the need for a Small Island Developing States-focused, -connected, and -driven process, and pledged to disseminate the results of the workshop to the appropriate regional seas programs and other organizations working on OA for further action.

Theme 7. Data management and integration

NOAA

The National Centers for Environmental Information (NCEI) serve as the NOAA OA data management focal point under the Ocean Acidification Data Stewardship (OADS) project. OADS provides dedicated long-term archival, online data discovery and access for a diverse range of data sets, including multi-disciplinary field observations, laboratory data, experimental data, and model data, for NOAA and its Federal partners. The National Centers for Environmental Information are uniquely qualified to fulfil this role, with a mission to preserve and steward oceanographic data across a wide variety of disciplines, and with the necessary technological infrastructure to serve the data to the community. The OADS project is envisioned as a building block towards a national OA data management and integration service required by the FOARAM Act.

Toward this goal, OADS developed a metadata content standard that is capable of accommodating OA data from moorings, research cruises, models, and laboratory or mesocosm studies on species response to OA. With the metadata template, OADS was able to establish metadata display templates that can best serve information about OA data sets to data users. OADS launched an OA data search portal in FY 2015 to allow users to discover and access OA data sets with ease. Base level data management (i.e., data come in, are properly documented, and served to the public) is fully functional.

As a higher-level data stewardship entity, OADS also strives to work on global synthesis products. In FY 2015, OADS published its first synthesis effort on the global distribution of aragonite saturation state. OADS staff plans to work on similar products for calcite saturation state and pH in the future.

Important data management advances also happened at the level of data generation. Scientists at the NOAA Atlantic Oceanographic and Meteorological Laboratory (AOML) made major contributions to the vetting and submission of data to the global Surface Ocean CO_2 Atlas. At the NOAA Pacific Marine Environmental Laboratory, technical staff conduct quality assurance and quality control on all data from the NOAA network of OA moorings. Pacific Marine Environmental Laboratory staff have developed software and management systems to do this work and easily deliver observational data that the Pacific Marine Environmental Laboratory collects to the national NOAA OA Data Management System.

SI

The Smithsonian Institution funded scientists and information technology experts located at the Smithsonian Environmental Research Center to design and develop a Data Acquisition and Management System for pCO_2, total alkalinity, and related chemical and physical measurements. This data system is aimed at organizing and applying uniform levels of quality assurance and quality control to similar data

collected across large geographic scales (i.e., across the Marine Global Earth Observatory network). Once vetted, SI will make these data available to interested parties and the public for download from a website.

National

Similar to global-scale OA projects, few OA research projects are truly national in nature. Thus, only a portion of the portfolio of Federal activities is considered "national" even though the entire portfolio builds knowledge useful for national application. National-level Federal activities on ocean acidification focused on development of technology for monitoring seawater chemistry, education and outreach, and the programmatic efforts needed to support Federal research and other activities on ocean acidification. Together, these activities build the Nation's capacity to tackle ocean acidification and enhance the public's awareness of why it is important to do address this challenge.

Theme 1. Research to understand implications of ocean acidification

USDA

In FY 2014 and 2015, USDA funded research and monitoring efforts targeted the anthropogenic atmospheric deposition of nitrogen, sulfur, and other compounds. Although the monitoring stations for this program were primarily land-based, these data can be used to extrapolate deposition of nitrogen and sulfur oxides that will make it into the ocean. Atmospheric deposition of nitrogen and sulfur oxides has a direct effect on pH, but also provides essential nutrients effecting primary productivity in the ocean and Great Lakes ecosystems. Additionally, USDA has several programs aimed at the reduction of nutrients going into the Nation's waterways. These nutrients eventually end up in the ocean, where they can cause algal blooms and create dead zones. USDA programs also focused on carbon sequestration, reduced emissions of greenhouse gasses, and the production of agriculture-based biofuels. Agriculture-based biofuels, such as woody biomass and algae, may reduce reliance upon fossil fuels. USDA has many other programs addressing indirect effects on OA. Specific projects funded in FY 2014 include but are not limited to:

- Studies on the stress physiology of aquatic species in a changing climate (including OA);
- Quantifying corals' adaptive capacity to OA using a mechanistic modeling framework;
- Understanding whether California's aquatic species have the necessary physiological resilience to respond to anthropogenic climate change stressors;
- Studying environmental and pathogen impacts on immune development in commercial aquaculture species;
- Developing methods to improve survival and maximize productivity and sustainability of Pacific shellfish aquaculture; and
- Examining synergistic effects of OA and the disease vibriosis on marine bivalve larvae.

Theme 2. Monitoring of ocean chemistry and biological impacts

NOAA

NOAA supported underway monitoring for OA and ocean chemistry on the NOAA Ships *Henry Bigelow*, *Ronald H. Brown*, and *Gordon Gunter*; the Merchant Vessel *Skogafoss*; the cruise ship *Explorer of the Seas*;

and the University-National Oceanographic Laboratory System ship *Walton Smith*. These ships transit throughout the Nation's waters.

Theme 4. Technology development and standardization of carbonate chemistry measurements on moorings and autonomous floats

NOAA

NOAA continued to develop state-of-the-art designs for laboratory systems to study species response to OA. NOAA laboratories have built a number of experimental systems capable of manipulating and controlling pH and pCO_2 with the accuracy and precision needed to conduct experiments relevant to addressing the impacts of OA on living marine resources. Some experimental facilities can also vary temperature and oxygen conditions, allowing assessment of species response to conditions expected under both OA and climate change scenarios. Building and maintaining these laboratories requires properly addressing demands related to engineering, chemistry, and biology, which can be highly challenging. NOAA staff act as a resource in laboratory design for much of the OA community.

NOAA's OA Program continued to support quality assurance and control for NOAA-funded carbon chemistry measurement by supporting activities at the Scripps Institution of Oceanography. Scripps staff evaluated and provided technical expertise on carbon chemistry analyses across NOAA and NOAA-affiliated labs that conduct OA research and monitoring. In doing so, NOAA helped refine best practices for conducting carbon chemistry analyses and evaluated the performance of the equipment used to do so. While NOAA does not explicitly fund the production of certified reference materials (i.e., measurement standards for carbon chemistry analysis), it did purchase a considerable amount of certified reference materials, thereby supporting their on-going production.

EPA

Because high frequency/high resolution measurements of carbon chemistry are needed in coastal waters, EPA scientists stayed engaged with sensing-technology developments. Where possible, EPA integrated state-of-the-art sensor technologies into existing National Estuary Program monitoring to identify potential impacts to these economically and ecologically important water bodies.

Theme 5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems

EPA

EPA is working to quantify the potential influence of OA on ecosystem services. Much of this work relies on EPA-supported projects that develop biophysical models and new methodologies to determine the economic and intrinsic value of coral reefs and shellfish. In FY 2015, EPA scientists assessed the ecosystem services that may be lost when shellfish beds in the Puget Sound (Washington) and the Gulf of Maine are affected by OA, and conducted research to assess the economic impacts of OA on United States mollusk fisheries. This latter project will help states identify control, mitigation, or adaptation options with favorable cost/benefit ratios.

Theme 6. Education, outreach, and engagement strategy on ocean acidification

NOAA

NOAA staff throughout the country engaged in a variety of OA-related education, outreach, and engagement activities in FY 2014 and FY 2015 (e.g., live and virtual tours for school groups, engagement with print, video, and online media developers). NOAA also trained many undergraduate students in OA research methodologies through the NOAA Hollings Scholar Program and other internship programs. A NOAA Education Implementation Plan, released in FY 2015, formalized the strategy behind NOAA's education and outreach work.

NOAA started the Sharing OA Resources for Communicators and Educators webinar series in FY 2014 and continued the series through 2015. This activity has reached over 1,100 participants to date. The webinar series provides OA communication tools to formal and informal educators and stakeholders across the country. One of its primary goals is to promote a more integrated and effective OA education community by sharing OA education and communication activities virtually. Fourteen webinars have been held to date; all are archived online on the NOAA OA Program website.

In FY 2014, NOAA hosted a workshop entitled "Effective Practices for Communicating OA" at the Ocean Sciences Meeting in Honolulu, Hawaii. This workshop focused on helping scientists improve their communication skills on OA, especially when interacting with non-technical audiences.

A number of NOAA websites include educational information about OA and links to resources, including presentations and scientific data. These websites include those developed by the OA Program, Pacific Marine Environmental Laboratory, Coral Reef Conservation Program, and the Channel Islands National Marine Sanctuary. The NOAA OA Program website had close to 35,000 visitors in FY 2015. Additionally, the OA Program maintains active Facebook and Twitter accounts, which reach hundreds of stakeholders every day.

A variety of NOAA offices developed summaries and explanations of OA and the science conducted to understand its progression and potential impacts. For example, the NOAA Geophysics Fluid Dynamics Laboratory has provided animations of historical and future OA, carbon fluxes, and aragonite saturation state for NOAA's "Science on a Sphere" and other outreach efforts.

Additionally, NOAA created an online forum with the purpose of refining messages and case studies about OA. This forum allows the communication and education community to stay abreast of OA research, which is rapidly expanding, and helps educators share educational activities and projects and information about their success and implementation.

NSF

In FY 2014 and FY 2015, NSF engaged in education and outreach activities that were not specifically focused on OA, but contributed to OA outreach. NSF also supported a wide range of education, training, and outreach efforts as part of broader impacts in individual research awards. Some of the outreach efforts included providing the fundamental science needed for decision-making.

NSF and NASA provide support for the Ocean Carbon and Biogeochemistry Project Office and its OA Subcommittee. The Ocean Carbon and Biogeochemistry Project supports community planning activities for OA and carbon cycling and engages in public outreach activities. With NSF support, the Ocean Carbon

and Biogeochemistry Project Office provided support for the 3rd United States Ocean Acidification Principal Investigator Meeting in June 2015. NSF also provided support for a Gordon Research Conference focused on Ocean Global Change Biology.

USGS

USGS presented research activities and findings through public presentations, websites, and a monthly newsletter titled *Sound Waves* that USGS distributes to the public, stakeholders, and state cooperators.

USDA

USDA informs the public on the results of research on new technologies geared toward reducing greenhouse gas emissions, nutrient runoff, and other programs aimed at reducing atmospheric CO_2 through carbon sequestration by agricultural soil conservation practices and best management practices. USDA shares information via workshops, on-farm extension programs, and online extension initiatives. USDA-funded Cooperative Extension natural resource and aquaculture field agents work closely with their Sea Grant Marine Advisory Service partners in providing science-based information on climate change and other factors that affect OA and its impact on their joint clientele in the aquaculture industry.

In February 2015, USDA organized a special OA-focused session at the Aquaculture America 2015 Conference in New Orleans, Louisiana. In this special session, NOAA provided a broad overview of the national OA program, and a representative from Taylor Shellfish, the Nation's largest commercial shellfish grower, gave the session attendees information on how lower pH water has effected the shellfish hatcheries on the United States West Coast. This information described methods that hatcheries can use to control losses in shellfish larvae due to OA and concomitant disease outbreaks. USDA gave a presentation on its many programs to reduce atmospheric CO_2 and nitrogen emissions from production agriculture thereby reducing runoff. University research scientists gave presentations on the effect of lowered pH on the survival and growth of larval marine fishes and shellfishes.

Theme 7. Data management and integration

NOAA

Working through the OADS project, the NCEI handles data management for all NOAA OA data relevant to United States and international waters. See Theme 7 under the Global section for a full description of both the basic activity and new developments at NCEI and at NOAA laboratories in FY 2014 and FY 2015.

NSF

The Biological and Chemical Oceanography Data Management Office handles data management for the NSF Biological and Chemical Oceanography Programs, as well some NSF wide activities such as Science, Engineering and Education for Sustainability Investment: Ocean Acidification. Oceanographic data are transferred to NCEI for permanent archival. The Long-term Ecological Research (LTER) network maintains a separate data management office.

Theme 8. Other ocean acidification research and monitoring activities

NOAA

NOAA spent $584K in FY 2014 and $1,134K in FY 2015 to support the NOAA Ocean Acidification Program Office, established in 2011 as directed by the FOARAM Act of 2009. This funding also covered administrative costs for NOAA OA research and outreach efforts within NOAA's Office of Oceanic and Atmospheric Research and the various laboratories and science centers to which the OA Program allocates funding. A key part of the OA Program's responsibility is to provide grants for research projects that explore the effects of OA on ecosystems and the socioeconomic impacts of increased OA. The OA Program incorporates a competitive, merit-based process for awarding grants.

USGS

Under the Energy Independence and Security Act of 2007 (P.L. 110-140), USGS has significant responsibilities to develop scientifically-based methods for assessment of biologic and geologic carbon-sequestration capacities, and to perform a comprehensive, nationwide resource assessment examining the full range of geothermal resources. As part of the efforts to fulfill this responsibility, USGS chairs an interdisciplinary carbon committee of scientists and managers. The committee is developing a long-term strategy for comprehensive assessment of carbon-sequestration resources, including the potential for new carbon sequestration and for conservation and enhancement of existing carbon-storage systems.

FWS

A large portion of the FWS contribution to ocean acidification reduction is the management policies that contribute to locally healthy ecosystems, which offer improved resilience to the effects of ocean acidification.

USDA

Although USDA has no programs specific to ocean acidification and the department does not have a primary role in the research and monitoring of ocean acidification as outlined in the *Strategic Plan for Federal Research and Monitoring of Ocean Acidification*, USDA-funded programs do address ocean acidification indirectly through programs addressing climate change and run-off of excess nutrients into the Nation's waterways. USDA provides for a few research, education, and extension activities and projects that are directly related to ocean acidification, such as effects of pH on the larvae of commercially produced shellfish and the production of new genetic lines of commercial shellfish that are resistant to pH changes. USDA activities that indirectly address ocean acidification include programs directed at:

- Improving air quality, such as reducing atmospheric deposition of nitrogen and sulfur oxide compounds as the result of burning fossil fuels and industrial processes;
- Understanding climate variability and climate change;
- Reducing nutrient runoff and emissions from concentrated animal feeding operations;
- Improving watershed management;
- Reducing fuel use in agriculture via improved agricultural practices;
- Carbon sequestration; and
- Maintaining and improving natural resources.

USDA is implementing on-farm energy efficiency outreach and technology transfer programs. These programs help farmers and ranch owners reduce input costs and their dependence on fossil fuels by using newly developed conservation and agricultural practices, such as no-till and Global Positioning System-guided precision agriculture systems, drip irrigation systems, and nutrient management plans for livestock producers that reduce water loss and nutrient runoff. USDA also released a Carbon Management Evaluation Tool to help livestock producers calculate how much carbon their land's soil and vegetation can remove and sequester from the atmosphere.

USDA does not have a funding authority for ocean acidification. Funding of directly or indirectly related projects depends on proposals submitted to USDA's core competitive programs, which provide an umbrella for this topical area. Other USDA funding of OA comes from USDA's core mission mandates but is subject to the budgets of the agencies implementing those programs.

United States Northeast

Research on ocean acidification in the United States Northeast grew rapidly in FY 2014 and 2015, signaling the larger recognition of and concern about the issue by regional stakeholders. Of particular note were the FY 2015 synoptic acidification-focused cruise of the North American East Coast and the initiation of projects to monitor ocean carbon chemistry conditions in shellfish hatcheries. The Northeast has led the Nation in studying how multiple simultaneous changes to ocean conditions (i.e., acidification, temperature change, deoxygenation, nutrient pollution) impact local species, particularly fish and bivalves. Some of this species-level research was scaled to the population level through modeling projects; in particular, a modeling project developed information useful for management of the highly-lucrative sea scallop fishery. FY 2014 and FY 2015 were major building years for the Northeast Coastal Acidification Network. The Network, which is supported in part by Federal agencies, serves as the leading organization for the synthesis and dissemination of regional OA data and information products in the United States Northeast.

Theme 1. Research to understand implications of ocean acidification

NOAA

NOAA maintains shared-user experimental facilities to study species response to OA at the Northeast Fisheries Science Center's Highlands, New Jersey, and Milford, Connecticut, laboratories. In FY 2014 and 2015, Northeast Fisheries Science Center staff conducted OA research on summer and winter flounder, black sea bass, scup, Atlantic surf clam, bay scallops, sea scallops, seven phytoplankton species from cultured strains, and natural phytoplankton communities from coastal Connecticut. NOAA funding supported Stony Brook University to study the response of hard clams and bay scallop adults and early life stages to OA. NOAA Sea Grant funded the following: University of New Hampshire scientists to study the impacts of OA and warming on clam viral disease dynamics; Smithsonian Institution and University of Connecticut scientists to study the impacts of OA and warming on Long Island (New York) benthic communities using mesocosms; and Woods Hole Oceanographic Institution scientists to study the impacts of transgenerational exposure to OA and warming on bay scallops.

NSF

NSF supported two ocean acidification-related awards in the Northeast in FY 2014 and FY 2015. Working in the Waquoit Bay (Massachusetts) salt marsh system, NSF-funded researchers are conducting an in-depth study of dissolved inorganic carbon and total alkalinity fluxes in an intertidal salt marsh and, in turn, how these dynamics impact carbonate chemistry and the carbon and alkalinity budgets in adjacent coastal waters. NSF-funded investigators are also examining how the multiple stressors of OA and hypoxia (low dissolved oxygen concentrations) will affect fitness of young Atlantic silverside. In addition, researchers are looking for transgenerational plasticity, or the passing of environmentally-induced acclimation from parent to offspring, as an adaptive response to low pH and/or oxygen.

EPA

In FY 2014 and 2015, EPA continued its work on biological responses to ocean acidification using seawater carbon dioxide manipulations, with a focus on improving the ecological relevance of laboratory experiments. EPA continued collaborating with the University of Rhode Island on studies of plankton community responses to acidification via CO_2 bubbling. EPA also continued its study of coastal acidification impacts on shellfish in Narragansett Bay, Rhode Island. To improve ecological interpretation, EPA intentionally synchronized this study with the current NOAA-funded study by Stony Brook University, with which EPA scientists are collaborating. The added EPA component focuses on experiments using field deployments of early-life-stage shellfish that have been pre-conditioned in EPA's laboratory-based CO_2 control system. Through its Science to Achieve Results (STAR) program, EPA funded a study at the University of Rhode Island focusing on the effects of elevated CO_2 and nutrients on marine communities and trophic interactions. Since nutrient-stimulated marine production can both affect and be affected by acidification, these and other related EPA activities are partly motivated by nutrient priorities in EPA's Safe and Sustainable Water Resources research program. Through these collaborations, which began in the previous reporting period, EPA scientists improved the basic ocean acidification literacy of FY 2015 national research planning intended to support Clean Water Act and Clean Air Act activities.

Theme 2. Monitoring of Ocean Chemistry and Biological Impacts

NOAA

NOAA engaged in monitoring ocean acidification in the Northeast using a variety of platforms. NOAA continued operating an OA mooring in collaboration with the Northeast Regional Association of Coastal Ocean Observing Systems (the United States Integrated Ocean Observing System (IOOS®) Northeast Regional Association) and the University of New Hampshire in the Gulf of Maine. NOAA also maintained underway OA observing equipment on a commercial ship that regularly transits between Boston, Massachusetts, and Iceland. In FY 2015, NOAA conducted a 34-day synoptic cruise of the North American East Coast from the Nova Scotia shelf to southern Florida on the NOAA ship *Gordon Gunter.* This cruise collected surface and subsurface OA measurements and other relevant oceanographic measurements. NOAA scientists partnered with NASA and EPA scientists to coordinate observations with the cruise, thus enhancing each other's work.

Throughout FY 2014 and 2015, NOAA funded carbon chemistry sampling during the Northeast Fishery Science Center's quarterly Ecological Monitoring cruises. These cruises collect a paired data set of carbon chemistry conditions and the abundance and distribution of plankton and fish species, and provide

complete coverage of the continental shelf along the United States East Coast from Cape Hatteras to the Gulf of Maine during the spring and fall. In addition, underway OA equipment has been installed on the NOAA ship *Henry Bigelow*. The equipment and data management are overseen by AOML and maintained by the NOAA Northeast Fisheries Science Center. The *Henry Bigelow* conducts fisheries independent trawl surveys that occupy United States Northeast waters at least once a year. Finally, with NOAA funding, researchers at Stony Brook University, along with colleagues from EPA, monitored summertime patterns of dissolved oxygen, pH, pCO_2, and the saturation state of aragonite in Long Island Sound and Jamaica Bay, New York.

NOAA Northeast Fisheries Science Center scientists worked with the Rutgers University shellfish hatchery in southern New Jersey to monitor the carbon chemistry conditions experienced by the hatchery. This shellfish hatchery produces disease-resistant seed oyster for the Delaware Bay oyster industry. NOAA also worked with the Barnegat Bay Partnership to set up EPA-funded OA monitoring equipment in central New Jersey.

NOAA funded a 3-year project by the University of New Hampshire to expand the quantity and quality of OA monitoring across Northeastern coastal waters, with the specific aim of meeting shellfish industry needs. Four different deployment platforms will be used to enhance OA monitoring within the Northeast region extending from Long Island Sound to the Scotian Shelf, with significant improvement in temporal and spatial coverage. These platforms will measure total alkalinity, pH, and pCO_2. Data products that will be developed from the multi-year measurements include nearshore and offshore baseline OA seasonal time series and threshold indices tied to acidification impacts on larval production at the Mook Sea Farm oyster hatchery in Maine.

NSF

The Pioneer Array, an element of NSF's OOI located between central New Jersey and Martha's Vineyard, Massachusetts, transitioned from construction to operational status late in FY 2015 and began releasing data for research in FY 2016. OOI assets will provide considerable data that will contribute to an increased understanding of OA.

NSF provided ongoing support for the Plum Island Ecosystem LTER site that collects time series data on carbon and nutrient cycling, biological communities, pH, and estuarine carbonate chemistry. NSF recently provided the Plum Island Ecosystem LTER site and other coastal LTER sites with funding supplements to improve their ability to monitor pH and carbonate chemistry.

EPA

EPA's sampling efforts in FY 2014 and FY 2015 focused on observations in coastal waters. EPA collaborated with Stony Brook University on a project that includes NOAA funding for laboratory studies of ocean acidification effects on resource shellfish species. Within the NOAA-funded project, EPA provided vessel support for joint sampling in Narragansett Bay, Rhode Island (noted in the *Third Report on Federally Funded Ocean Acidification Research and Monitoring Activities*), and continues to provide in-kind ecological modeling support. To leverage and capitalize on the timing of this project, EPA funded a separate field experiment in FY 2014 through FY 2015 to examine *in situ* shellfish responses to ocean acidification based on results from the laboratory studies. Field sampling of carbonate chemistry during this experiment will shed light on fine-scale spatial variation in estuarine acidification.

In FY 2015, EPA added carbonate parameters to its monthly nutrient and stable isotope surveys of Narragansett Bay, certain stations of which overlap with the NOAA-supported Stony Brook University collaboration with EPA described above. Although infrequent and spatially coarse, these surveys are intended to document Narragansett Bay's biogeochemical response to recent reductions in nutrient loading. This "natural experiment" serves as a representative site within the United States East Coast portion of EPA's research on nutrient-enhanced coastal acidification and hypoxia. To address sampling gaps on the United States inner continental shelf, EPA and NOAA worked to synchronize EPA's monthly survey of Narragansett Bay with the FY 2015 NOAA-funded synoptic cruise of the North American East Coast described above.

EPA also provided capital support for instrumentation at other sites in the Northeast through its National Estuary Program, including a monitoring system for pH and pCO_2 that began operation in the Casco Bay National Estuary Program (Maine) study area. Funding to the National Estuary Program in Long Island Sound and Barnegat Bay (New Jersey) supported the procurement of similar monitoring systems.

NPS

NPS's Acadia National Park (Maine) is working with the Schoodic Institute and other partners to investigate the impacts of climate change and OA on intertidal ecosystems. Acadia National Park deployed sensors and engaged professional scientists and citizen science volunteers to study physical changes (e.g., pH, temperature, dissolved oxygen) and changes in the abundance, distribution, phenology, and interaction (e.g., predator-prey) of intertidal species. The park is using scenario planning to identify best actions for addressing OA.

Theme 3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms

NOAA

In FY 2014 and 2015, NOAA funded oceanographic and ecological modeling related to OA in the Northeast, including climatology of OA in the Northeast continental shelf region using data from the 1980s to the present. The climatology characterizes seasonal and regional variability, which can then be used to track whether current changes in ocean carbon chemistry are within the normal range of variability for the region or whether the changes are outliers. NOAA explored the impacts of OA on the Northeast marine ecosystem using an Atlantis ecosystem model, in addition to a structured process to estimate the vulnerability of Northeast fisheries species to climate change and OA. NOAA also funded a research group at Woods Hole Oceanographic Institution and NOAA colleagues to develop a linked set of biogeochemical, population, and bioeconomic models for sea scallops. With this modeling suite, the researchers studied the impacts of OA and warming on population dynamics and harvest, and how various management strategies might perform under changing environmental conditions. Finally, NOAA funded Stony Brook University scientists to develop models to assess the population level impacts of OA on hard clams and bay scallops.

EPA

EPA collaborated with Stony Brook University on the above-described shellfish study, providing in-kind ecological modeling support. In addition, EPA scientists incorporated carbonate chemistry into the water quality models used for research on the impacts of nutrient loading to coastal ecosystems.

NASA

A NASA modeling project is examining the variability of acidification in coastal Gulf of Maine waters. This project aims to improve understanding of processes controlling carbonate system variability in coastal areas by combining monitoring data, process studies, numerical modeling, and ocean color satellite data. Specific questions this project is answering include: (1) what are characteristic temporal and spatial scales for physical and biological processes that affect the surface carbonate system in the coastal ocean; (2) what is the relative importance of individual processes, such as lateral mixing and net community productivity, on the carbonate system in a continuum from land to the open ocean; (3) is it possible that such processes combine synergistically to increase acid stress or antagonistically to create spatiotemporal refuges from acid stress; and (4) is the carbonate system in the coastal Gulf of Maine in quasi-static steady state (no significant sources and sinks), a dynamical steady state (sources and sinks are in balance), or randomly determined. The project team is using models and satellite data to distinguish how biological and physical processes regulate the carbonate system of coastal waters. Using output from a high-resolution general circulation model, the team can track carbonate species and biological variables from fresher coastal waters into the open ocean boundary. NASA funded this work as part of the Carbon Cycle Science program.

Theme 4. Technology development and standardization of carbonate chemistry measurements on moorings and autonomous floats

NOAA

In FY 2015, NOAA and IOOS awarded a 3-year grant to the University of New Hampshire to introduce and refine a new technology for measuring total alkalinity. An outreach and technical supervision component of the project will transfer carbonate system observing technologies to project partners, the broader fishing industry, and the resource management and science communities.

EPA

The high cost of instruments for carbonate system measurements continues to prohibit the high sampling frequency and spatial resolution that may be necessary in dynamic nearshore environments (i.e., less than 5 kilometers from shore) that are of concern to many stakeholders. These environments are generally not the focus of precision-oriented oceanographic instrument developers. As resources allow, EPA is opportunistically investigating and comparing available low cost alternatives for both handling and analysis of seawater samples that could conceivably be used in the 2020 National Coastal Condition Assessment.

As part of its FY 2014 and FY 2015 shellfish field experiments described under Theme 1 of the United States Northeast section, EPA developed a field assay technique for monitoring the growth of hard clams (*Mercenaria mercenaria*) with known histories of controlled ocean acidification exposure.

Theme 5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems

NOAA

NOAA supported the Northeast Fisheries Climate Vulnerability Assessment that examined the vulnerability of 82 fish and invertebrate species in the region to climate change, including ocean acidification. The Northeast Fisheries Climate Vulnerability Assessment has been linked to NOAA Fisheries Social Indicators to examine the climate vulnerability of coastal communities in the Northeast.

NOAA continued funding two projects that use results from laboratory studies on species sensitivity to OA and an understanding of local carbon chemistry conditions to project future population dynamics of species targeted in wild fisheries (e.g., hard clams, bay scallops, sea scallops). Both efforts address potential future changes in fisheries. For the sea scallop project, an Integrated Assessment Model was developed to project landings by the United States sea scallop fishery under different carbon emissions scenarios. The model includes submodels on the basic biology of the sea scallop, regional biogeochemistry, and socioeconomics. Researchers began developing a web-based decision-support dashboard that allows interactive exploration of model output under various scenarios.

Theme 6. Education, outreach, and engagement strategy on ocean acidification

Multiagency

FY 2014 and FY 2015 were major building years for the Northeast Coastal Acidification Network (NECAN). NECAN serves as the leading organization for the synthesis and dissemination of regional OA data and information products in the United States Northeast. The network provides rigorous and balanced scientific information to regional decision makers and user groups regarding the current state of knowledge of OA and its potential environmental and socioeconomic impacts to the Northeast region. The network also coordinates and develops regional priorities for science observing and research investments designed to further understanding of OA in a way most responsive to user requirements. NECAN is a joint Federal, academic, and industry partnership established under the Northeast Regional Association of Coastal and Ocean Observing Systems.

In FY 2014, NECAN hosted a webinar series with 16 talks to develop the state of the science on OA for the Northeast region and share scientific findings with interested academics and stakeholders. Following the webinar series, NECAN hosted a State of the Science Meeting that focused on what is known and not known about OA in the region, how to engage with stakeholders, and how to move forward to fill knowledge gaps. The journal *Oceanography* published this information in FY 2015, and a more comprehensive technical memorandum is being developed. NECAN organized and hosted state-level stakeholder meetings to disseminate the state of the science and hear the interests and questions of industry, local governments, non-governmental organizations, and other concerned citizens. In FY 2015, these meetings occurred in Maine, Massachusetts (north shore and south shore), and Rhode Island. Meetings occurred in the Long Island Sound region and Canada's Maritime Provinces in FY 2016. NOAA and EPA provided funding and in-kind support for the NECAN workshops and other efforts during FY 2014 and FY 2015.

NOAA

NOAA Sea Grant funded the Massachusetts Institute of Technology to work with coastal communities, land managers, and marine industries in preparing for future impacts of climate change, including OA. The researchers solicited information on the current state of knowledge and knowledge needs from Massachusetts constituents, and developed specific research goals and products, outreach activities, and educational products and activities based on stakeholder input and current, regionally-specific science.

United States Mid-Atlantic

Activities in the United States Mid-Atlantic region in FY 2014 and 2015 focused on the Chesapeake Bay. Increased monitoring and modeling of Chesapeake Bay carbon chemistry built better understanding of the highly variable and complex conditions in this shallow, nutrient-enhanced estuary. Regional research studies of species response explored how complex environmental dynamics affect shellfish and fish.

Theme 1. Research to understand implications of ocean acidification

NOAA

In FY 2014 and 2015, the NOAA Northeast Fisheries Science Center's Howard Marine Laboratory, located in the Mid-Atlantic region in Highlands, New Jersey, conducted OA research on the following Mid-Atlantic region species: summer and winter flounder, black sea bass, scup, Atlantic surf clam, bay scallops, and sea scallops.

NSF

NSF supported two ocean acidification-related awards in the Mid-Atlantic in FY 2014 and FY 2015. One NSF Collaborative Research project is evaluating planktonic microbial responses to multiple stressors along a transect from a Mid-Atlantic temperate estuary into the Sargasso Sea. The other NSF Collaborative Research project is examining diurnal, seasonal, and interannual variability of the CO_2 system in the Chesapeake Bay to gain insights about the multiple factors that influence the pH regime in non-pristine estuarine systems.

SI

Investigators at the Smithsonian Environmental Research Center (Chesapeake Bay, Edgewater, Maryland) are examining patterns and effects of diel-cycling acidification and hypoxia typical of shallow waters of the Chesapeake Bay and coastal systems worldwide. As with other global change drivers, OA occurs in concert with other environmental stressors. Because aerobic respiration of aquatic organisms both consumes oxygen and produces CO_2, hypoxia and acidification tend to co-occur. To conduct experiments that mimic environmentally realistic exposures, researchers have developed a computer-controlled laboratory facility. In FY 2014 and FY 2015, experimental work using this facility focused on growth, filtration, and disease dynamics of oysters, and growth and tolerance of two related fish species, the Atlantic silverside and inland silverside. Experiments indicated that cycling acidification alters the immune response of adult oysters and reduces growth of juvenile oysters, but that growth effects may be reduced or reversed in long term exposures, in part as a result of stimulated filtration rates. For fish, short-term

exposure to acidified conditions affected predator avoidance behavior and increased sensitivity to hypoxia by depressing breathing rate.

Theme 2. Monitoring of ocean chemistry and biological impacts

NOAA

Part of the FY 2015 34-day synoptic cruise of the United States East Coast on the NOAA ship *Gordon Gunter*, described under Theme 2 of the United States Northeast section, was devoted to Mid-Atlantic sampling. The cruise included surface and subsurface OA sampling and measurement, and assessment of other relevant oceanographic measures. NOAA, NASA, and EPA scientists collaborated to coordinate other observations with the cruise, which increased the value of the monitoring data collected by all groups. As noted under Theme 2 of the United States Northeast section above, NOAA installed underway OA equipment on the NOAA ship *Henry Bigelow*. The ship conducts fisheries independent trawl surveys, which occupy Mid-Atlantic waters at least once a year. The carbon chemistry sampling during the Northeast Fishery Science Center's quarterly Ecological Monitoring cruises as described under Theme 2 of the United States Northeast section collect a paired data set of carbon chemistry conditions and the abundance and distribution of plankton and fish species. These cruises provide complete coverage of the continental shelf along the East Coast from Cape Hatteras to the Gulf of Maine during the spring and fall.

EPA

In both FY 2014 and FY 2015, EPA reoccupied ocean acidification sampling transects identified in the *Third Report on Federally Funded Ocean Acidification Research and Monitoring Activities* for the Mid-Atlantic Bight using contracted ship time. These transects were primarily located in the shelf plumes of Chesapeake Bay and Delaware Bay. Ocean acidification sampling was fully paired with nutrient sampling and analysis to support EPA's research activities on nutrient-enhanced coastal acidification and hypoxia. Similarly, EPA conducted extensive nutrient and ocean acidification sampling in Delaware Bay in FY 2014 and FY 2015.

Theme 3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms

NOAA

NOAA funded researchers from the University of Maryland, University of Delaware, and Oregon State University to advance numerical modeling tools for the Chesapeake Bay. The purpose of the work was to simultaneously simulate the dynamics of eutrophication, hypoxia, carbonate chemistry, and oyster reef growth and interaction with the water-column under present and future conditions.

EPA

EPA conducted nutrient and carbonate chemistry surveys in Delaware Bay as part of a broader modeling effort to develop evaluations of estuarine habitat quality.

Theme 6. Education, outreach, and engagement strategy on ocean acidification

Scientists at the NOAA Northeast Fisheries Science Center developed a stand-alone automated, interactive OA education display that is used at the NOAA Howard Marine Laboratory (Highlands, New Jersey) and may soon be set up at a local aquarium.

United States Southeast and Gulf Coast

Federal activities related to ocean acidification in the United States Southeast and Gulf Coast regions focused on ecosystems in which species create the major habitat (i.e., coral reefs, seagrass meadows) and on the links between acidification and hypoxia in the region. These activities build the information base for conducting vulnerability assessments of communities and stakeholder groups to ocean acidification while acknowledging that acidification is one of many challenges in the region. With Federal support, the Southeast Ocean and Coastal Acidification Network launched in FY 2014 to support and encourage discussions on ocean and coastal acidification in the Southeast region.

Theme 1. Research to understand implications of ocean acidification

NOAA

NOAA's research in the Southeast for FY 2014 and FY 2015 focused on primary producers and coral species. NOAA Sea Grant funded Old Dominion University scientists to study the impacts of OA and warming on the eelgrass *Zostera marina*. NOAA's Coral Reef Conservation Program supported field-based research activities in Florida to understand the response of coral growth and calcification across natural gradients in CO_2. These projects studied how different coral reef communities respond to differing CO_2 environments and assessed if natural buffering mechanisms (e.g., seagrass CO_2 uptake) could be utilized to maximize production and outplant success in the restoration of *Acropora* coral, an Endangered Species Act-listed species.

NSF

NSF provided support for two projects in the Southeast in FY 2014. NSF-funded researchers are conducting comprehensive physiological studies on five species of calcifying and five species of non-calcifying macroalgae to test the hypothesis that under OA and warmer sea surface temperatures, fleshy macroalgae are likely to predominate in tropical reef and lagoon communities. The other NSF-funded project is determining how different genotypes of the coral *Acropora cervicornis* from Florida reef systems differ in response to OA, disease resistance, and resilience to increased temperatures. A trait-based model will incorporate information about trade-offs among different coral phenotypes and be used to predict whether there seems to be sufficient variation within this species for survival under future climate conditions.

SI

At the Smithsonian Marine Station (Indian River Lagoon, Fort Pierce, Florida) researchers used a series of carefully controlled aquaria to examine how reduced pH and increased temperature influence the growth and physiology of calcified green algae. This particular group of algae represents an important component of many marine environments, and provides numerous ecological benefits such as habitat provisioning

and sediment production. Data from these experiments contribute to understanding of the responses of reef calcifiers to climate change and decreasing ocean pH. Researchers from the Smithsonian Marine Station's Chemical Ecology Lab tested the combined effects of OA and algal overgrowth, two of the most prominent threats to coral health, on the health of adult corals and the settlement and survival of juvenile corals. While the responses of corals to these threats have been studied individually, corals are likely to experience a combination of OA and algal overgrowth in the near future. Over the course of two years, a series of experiments examined the combined impacts of OA and different species of macroalgae on the health and recruitment processes of multiple coral species. Short-term exposure to OA alone had little effect on the health of adult corals, settlement, or survival of juvenile corals but exposure to certain species of macroalgae in addition to exposure to OA caused bleaching and reduced coral photosynthetic potential, and had variable effects on settlement and juvenile survival. These studies demonstrate the complexity of coral responses to different stressors and highlight the importance of evaluating environmental stressors in combination.

USGS

In FY 2014 and 2015, USGS analyzed carbon data from the Gulf of Mexico in collaboration with researchers from NOAA and academia and as part of a NASA-led effort on coastal carbon synthesis. USGS measured carbon chemistry of the West Florida Shelf as a cooperator in this project to address ocean acidification in the Gulf of Mexico. The USGS St. Petersburg (Florida) Carbon Analytical Laboratory also participated in inter-comparison quality control projects with other Federal laboratories and academia to assure the quality of carbon chemistry measurements.

USGS supported studies that evaluated coastal carbon fluxes and submarine groundwater discharges, which act as stressors on coral reefs and other ecosystems. These studies included syntheses of historical data of carbon fluxes and carbonate chemistry from inland Florida springs to coastal sites. USGS developed numerical modeling systems for the flow patterns of and discharge rates into Biscayne Bay, Florida, which may provide insight into causes of ecosystem degradation.

USGS and NSF supported studies in FY 2014 and FY 2015 that compared historic calcification rates with current rates, with the goal of modeling future rates. In addition, USGS established a new time-series field site on a reef in the Florida Keys, and continued supporting work initiated in 2009 that focuses on the synthesis of historical physical and chemical records at shellfish bed sites within Florida to provide a regional view of ocean acidification.

EPA

In FY 2015, EPA initiated new biological response experiments focusing on the combined effects of coastal acidification and hypoxia on marine organisms at its research laboratory in Gulf Breeze, Florida. This effort funded a postdoctoral researcher and equipment.

Theme 2. Monitoring of ocean chemistry and biological impacts

NOAA

NOAA engaged in monitoring ocean acidification in the United States Southeast using a variety of asset types. The FY 2015 NOAA-led synoptic cruise of the United States East Coast on the NOAA ship *Gordon*

Gunter covered the Southeast Atlantic coast and part of the Gulf of Mexico. See Theme 2 under the United States Northeast section for additional information. NOAA operated OA moorings at Gray's Reef, Georgia; Cheeca Rocks, Florida; and coastal Mississippi. Work on a Flower Garden Banks National Marine Sanctuary (Texas) OA mooring began in FY 2015. In late FY 2015, NOAA and the University of Southern Mississippi conducted a 3-month, multi-platform OA and hypoxia study that included a prowler mooring with a novel dissolved inorganic carbon sensor, sail drones, and two density gliders. The project collected a variety of OA-relevant data at the surface and at depth. In FY 2014 and FY 2015, NOAA monitored the status and trends of coral reefs in Florida by establishing a sentinel site for OA in the Florida Keys and monitoring the progression and impacts of OA at non-sentinel sites in the Florida Reef Tract and at Flower Garden Banks. The next scheduled synoptic OA survey of the Gulf of Mexico is in the planning phase and will occur in FY 2017.

BOEM

Initiated in FY 2014, a joint BOEM Environmental Studies Program, NOAA, and Texas A&M University 5-year project established the Flower Garden Banks National Marine Sanctuary as a coral reef OA sentinel site. BOEM's Environmental Studies Program conducts ocean research to provide science in support of decisions regarding oil and gas, marine-mineral, and renewable-energy leasing of the United States outer continental shelf. With matching resources provided by the Shell Exploration and Production Company, the project will establish both chemical and biological monitoring within the Flower Garden Banks National Marine Sanctuary to better understand how this system is changing and what attribution, if any, can be ascribed to OA. This study will aid BOEM's role in understanding the multiple factors impacting the Flower Garden Banks ecosystem. Questions to be answered by the study include: what are the present temporal (i.e., diurnal to interannual) and spatial trends in ocean acidification-related parameters, as measured through saturation state dynamics, in Flower Garden Banks reef waters; what are the primary driving controls of observed variability in the carbonate chemical dynamics; and have significant changes occurred in these dynamics since the inception of the Flower Garden Banks Long-Term Monitoring Program.

NSF

NSF provided ongoing support for the Virginia Coastal Reserve LTER and Georgia Coastal Ecosystem LTER. Both of these sites collect time series data on carbon and nutrient cycling, biological communities, pH, and estuarine carbonate chemistry.

EPA

EPA provided funding to the Coastal Bends Bay National Estuary Program (Texas) for the procurement of a pH and pCO_2 monitoring system.

USGS

USGS programs for FY 2014 and FY 2015 were aimed at determining the baselines and thresholds of various coral reef communities to changes in pCO_2, calcium carbonate saturation state, and ocean acidification by measuring coral reef metabolic and calcification rates. Furthermore, studies on endangered species prompted the establishment of five monitoring sites within Biscayne and Dry Tortugas National Parks (Florida) in partnership with NPS, and the Florida Keys National Marine Sanctuary in

partnership with NOAA, to provide information on calcification rates of corals and the potential relationship with climate change and ocean acidification.

Theme 3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms

NOAA

NOAA funded University of Miami and NOAA scientists to use a high-resolution regional ocean-biogeochemistry model to study the biogeochemistry of the United States East and Gulf Coasts. This model is being used to examine future OA variability in the East and Gulf Coasts and provide an observational strategy suitable for elucidating the multi-annual trend of carbon and biogeochemical variables in the two regions. NOAA also funded Texas A&M University to model the relationships between estuarine acidification and other stressors (i.e., reduced freshwater inflow, hypoxia, nutrient loading) in Texas estuaries. This project aims to provide information on how changes in water flow may cause hypoxia and short-term OA in Texas estuaries.

EPA

EPA scientists incorporated carbonate chemistry into the water quality models used for research on the impacts of nutrient loading to coastal ecosystems.

USGS

As part of a NASA-funded coastal carbon synthesis effort, USGS collaborated with academia and NOAA in modelling carbon fluxes and ocean acidification in the Gulf of Mexico using a synthesized dataset from oceanographic cruises. Database products developed by this synthesis are being used for follow-on investigations.

Theme 6. Education, outreach, and engagement strategy on ocean acidification

NOAA

In FY 2014, the Southeast Coastal and Ocean Observing Regional Association (the IOOS Southeast Regional Association) and NOAA founded the Southeast Ocean and Coastal Acidification Network (SOCAN) to support and encourage discussions on ocean and coastal acidification in the Southeast region. SOCAN aims to enhance collaborations and communications throughout the region on ocean and coastal acidification regional drivers, approaches to monitoring, state of the science, and vulnerable species and ecosystems. SOCAN has hosted 17 webinars to date, most in FY 2015, to develop the state of the science in the region and build a community of OA researchers. These webinars are archived online and publically available on the SOCAN website.

United States West Coast

The majority of Federal activities on ocean acidification take place on the United States West Coast, a region where ocean waters are acidified through natural processes and enhanced with anthropogenic emissions. The shellfish industry in this region already has experienced the impacts of OA. Federal agencies conducted robust activities on all seven themes of the *Strategic Plan*, providing an example for

the Nation of comprehensive action on ocean acidification. Many of these activities were designed to directly inform decision-making now and in the future. A hallmark of the community of scientists working on ocean acidification along the West Coast is their collaborative nature, which results in coordinated activities and development of complementary information.

Theme 1. Research to understand implications of ocean acidification

NOAA

NOAA built a new state-of-the-art facility to study species response to OA, hypoxia, and climate change at the Northwest Fisheries Science Center field station in Mukilteo, Washington. Northwest Fisheries Science Center scientists studied the response of Dungeness crab, geoduck, pteropods, China rockfish, and Pacific krill to OA conditions in the laboratory. NOAA's field-based OA investigations on the West Coast found wild pteropods with partially dissolved shells, likely from the acidified conditions that occur along the United States West Coast.

NOAA has invested in a number of aquaculture and shellfish-focused projects along the West Coast, with funding provided to the following:

- Cultured Abalone Farm to develop commercial lines of red abalone that are resistant to OA;
- Catalina Sea Ranch to develop genetics-based selective breeding protocols for the Mediterranean mussel to advance aquaculture under OA;
- Oregon State University to improve juvenile oyster survival via adaptation strategies to OA and to develop metrics of acidification stress for commercially important bivalves;
- University of Washington to study the response of a variety of commercial shelled mollusk species and two crustacean zooplankton species to OA conditions; and
- University of California, Santa Cruz, to study rockfish response to OA conditions.

NOAA also invested in OA research on primary producers, including support for University of Southern California scientists to study *Pseudo-Nitzschia* bloom toxicity under OA conditions and the trophic transfer of domoic acid in food webs exposed to OA conditions. NOAA researchers worked with colleagues from the University of Washington, Puget Sound Restoration Fund, and Washington Department of Natural Resources to assess whether cultivated seaweed can protect shellfish and other sensitive species from OA.

NSF

NSF provided support for eight OA-related projects in FY 2014 and two projects in FY 2015 along the United States West Coast. Studies focused on the effects of OA, and usually multiple stressors, on abalone, rockfish, gastropod larvae, and other invertebrate larvae. Another NSF-funded project is examining the effects of OA on intertidal calcifying algae and, in turn, the role of these algal forms on intertidal community structure.

NPS

NPS is working with partners to use field data collected in national parks to inform OA experiments. At Point Reyes National Seashore (California), a three-pronged approach is being used to address OA, including: (1) modern ocean monitoring and past ocean reconstructions to quantify changes in seawater

chemical properties over multiple timescales; (2) laboratory experiments to determine impacts of OA on larval, juvenile, and adult life stages of marine species; and (3) moving animals exposed to OA conditions in the laboratory to the field to evaluate potential consequences of OA accruing in the real world. Channel Islands National Park (California) has teamed up with the University of California, Santa Barbara, to collect pH data generated by SeaFETs sensors. These data help inform laboratory-based experiments assessing the effects of OA on marine organisms, and increase understanding of near-shore ocean chemistry.

EPA

EPA funded two ocean acidification studies on the United States West Coast through its STAR program. One of these studies focused on the effects of OA on estuarine phytoplankton dynamics. The other study focused on the response of the shellfish toxic pathogen *Vibrio tubiashii* to changes in CO_2, dissolved oxygen, and temperature.

Theme 2. Monitoring of ocean chemistry and biological impacts

NOAA

NOAA operated coastal OA moorings in Washington, Oregon, and Southern California, and open-ocean OA moorings off Southern California and in the central northeast Pacific Ocean. NOAA also operated other OA monitoring at the Olympic Coast National Marine Sanctuary (Washington). In FY 2015, NOAA began planning for a synoptic OA cruise of the North American West Coast from the northern Baja California Peninsula to the top of Vancouver Island; the cruise occurred in the summer of FY 2016. NOAA's Northwest Fisheries Science Center continued to conduct a zooplankton time-series study off of Newport, Oregon and, with the NOAA Pacific Marine Environmental Laboratory, collected water samples to relate zooplankton species abundance with carbon chemistry. NOAA also supported work to correlate zooplankton species abundance with carbon chemistry in Puget Sound, Washington. Finally, NOAA maintained underway CO_2 systems on the NOAA ships *Oscar Dyson* and *Bell M. Shimada,* which operate in the California Current Ecosystem, Gulf of Alaska, and Bering Sea.

NSF

The Coastal Endurance Array, an element of NSF's OOI located off the coast of Oregon and Washington, transitioned from the construction phase to operational status late in FY 2015. OOI began releasing data for research use in FY 2016, including measurements relevant to studies of OA.

NSF continued to support the Santa Barbara Coastal LTER site, with contributing support for OA-related measurements. NSF also supported OA-related observations at the California Current Ecosystem LTER site. NSF also provided ship time support for the California Current Ecosystem LTER, not included in the amounts listed in the Appendix. The California Current Ecosystem LTER has strong collaborative ties and a joint sampling program with the California Cooperative Oceanic Fisheries Investigation (CalCOFI) program, a partnership that conducts quarterly oceanographic monitoring off of Southern and Central California.

EPA

EPA provided funding to the Santa Monica Bay National Estuary Program (California) for the procurement of a pH and pCO_2 monitoring system. EPA also formed a cooperative agreement with the Washington

State Department of Ecology to study the role of nutrients in acidification conditions in Puget Sound, Washington. Funding supported the development of a source attribution model for Puget Sound to understand the contributors to acidified conditions in this body of water. In FY 2015, EPA began a study focused on carbonate chemistry dynamics in nearshore shellfish habitat in Puget Sound. This EPA-funded study focused on identifying local factors influencing carbonate chemistry dynamics and is a collaboration between EPA, USGS, Oregon State University, the State of Washington, and Tulalip Tribes.

BOEM

Under its Environmental Studies Program, BOEM contributed to knowledge about OA through research taking place in the Pacific Ocean. The Pacific Regional Intertidal Sampling and Monitoring team, a group of biologists within the BOEM Pacific Region, maintained an ocean monitoring station within the Channel Islands National Park's boundaries on Anacapa Island, California. The continued monitoring of ocean pH, temperature, and salinity at this site is a partnership with a broader network of state and Federal agencies and university groups aiming to track ocean acidification along the United States Pacific Coast.

NPS

NPS monitored OA in several locations along the United States West Coast. Cabrillo National Monument (California) worked to develop an OA monitoring program to assess what changes in ocean pH may be occurring in protected intertidal habitat. Coupling the long-term intertidal monitoring observations with locally collected OA data will provide managers and researchers with the tools they need to understand the impacts of climate change on intertidal systems, which are often called the nursery of the sea.

Olympic National Park (Washington) has monitored OA at two intertidal sites on the remote outer Pacific Coast since 2010. The goals of the program are to characterize the status and dynamics of nearshore carbonate system parameters, along with other parameters associated with carbonate system controls (e.g., temperature, salinity, nutrients, chlorophyll a). In 2015, the OA monitoring capabilities were significantly upgraded with state-of-the-art pH sensors and analytical laboratory equipment for pH and total alkalinity determination. OA dynamics will be compared to the dynamics in a long-term data set of the intertidal community to provide park managers with insight on the effects of climate change on one of the most biodiverse intertidal assemblages on the United States Pacific Coast.

San Juan Island National Historical Park (Washington) began monitoring OA and associated carbonate system parameters in the intertidal zone of the park's American Camp unit in 2015 based on state-of-the-art pH sensors. This effort is an expansion of the Olympic National Park OA program to compare differences in the status and dynamics of the nearshore carbonate system between the developed inland Salish Sea and the remote outer Pacific Coast. OA trends and long-term rocky intertidal community monitoring data at the American Camp unit will also be compared to provide managers with insight into local climate change impacts.

Theme 3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms

NOAA

NOAA funded a number of oceanographic modeling projects related to OA in the California Current region, including the development of algorithms based on temperature and oxygen measurements to derive

estimates of seasonal dynamics in OA. These algorithms are intended for application to legacy data sets, such as those the National Marine Fisheries Service collects in their annual transects, and could expand historical knowledge of OA in certain regions. NOAA also funded development of projections of OA using a California Current Regional Ocean Model. NOAA-collected observations of ocean carbon chemistry are contributing to this effort and development of a Pacific Northwest Regional Ocean Model. Finally, NOAA funded work using this Pacific Northwest Regional Ocean Model to develop seasonal forecasts of OA and hypoxia.

NOAA also supported a number of ecological modeling projects related to OA in the California Current region. NOAA funded University of Washington, NOAA, and Australian scientists to model the potential impacts of OA on the California Current food web using a sophisticated model that incorporates geophysical data and is linked to a fisheries economics model. This effort will project changes in yield and fisheries revenue at a regional level, and will assess various management strategies under OA. NOAA scientists also collaborated with the Department of Energy's Pacific Northwest National Laboratory to investigate how the diel movements of zooplankton in the Puget Sound, Washington, influence their CO_2 exposure under current and projected future conditions, information that is important for properly parameterizing laboratory experiments.

NOAA Sea Grant funded the following:

- University of California, Davis, to study how coastal upwelling affects carbon chemistry conditions in San Francisco Bay;
- Oregon State University to understand, forecast, and communicate the linkages between OA and hypoxia in Oregon's coastal ocean; and
- University of California, Santa Cruz, to develop a methodology for using boron isotopes to study past acidification conditions in the coastal California.

Theme 4. Technology development and standardization of carbonate chemistry measurements on moorings and autonomous floats

NOAA

In FY 2014 and FY 2015, work on an IOOS and NOAA grant that supports OA sensor development and application targeted to the shellfish industry began across the United States West Coast, Alaska, and Hawaii. Specifically, the project: (1) developed and applied state-of-the-art monitoring technologies relevant to shellfish hatcheries and growers in Washington and Oregon; (2) applied and tested new observing technologies for OA observing on deep water moorings off of Washington and Oregon; (3) tested beta aragonite saturation state prototype monitoring equipment at shellfish hatcheries; and (4) tested a remotely deployable, prototype dissolved inorganic carbon analyzer at a new buoy off of Hawaii.

In FY 2015, NOAA began a second West Coast-focused technology project to evaluate the best carbon system technologies to deploy in subsurface waters, demonstrate the utility of these enhanced observations on ocean moorings, and make recommendations on how advanced technologies can be incorporated into OA monitoring programs. Field work for this project will occur at the La Push mooring off Washington State starting in 2017.

Theme 5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems

NOAA

NOAA supported a project to assess the sociocultural vulnerability and resilience of tribal and non-tribal coastal communities to OA in Washington State. Findings will identify vulnerability from OA-anticipated impacts to indigenous-defined aspects of health and community wellbeing.

NOAA also funded a variety of projects related to shellfish production under ocean acidification. NOAA Sea Grant funded four projects on OA related to oyster aquaculture and restoration at the University of California, Davis; Oregon State University; and University of Washington, and one project related to wild and farmed mussels at the University of Washington. Through its Saltonstall-Kennedy grant program, NOAA also funded the Pacific Shellfish Institute to quantify the functional relationships between shellfish culture and seagrass in West Coast estuaries. This research will inform regulatory decisions and help the shellfish industry and resources managers understand if seagrasses can help mitigate some impacts of OA on wild and harvested shellfish. NOAA Sea Grant also funded projects at the University of California, Davis, on the influence of seagrass on estuarine acidification and at Oregon State University on shellfish. In addition, NOAA Sea Grant has funded work at the University of Washington on marine protected areas in Puget Sound, Washington, that examines the threats from OA.

Theme 6. Education, outreach, and engagement strategy on ocean acidification

Multiagency

The California Current Acidification Network (CCAN), launched in 2010, continued to create a community of OA stakeholders along the United States West Coast in FY 2014 and FY 2015. A number of Federal agencies participate in CCAN. In FY 2015, CCAN hosted three webinars, each of which was jointly given by a scientist and an industry representative.

NOAA

NOAA participated in the West Coast Ocean Acidification and Hypoxia Panel in FY 2014 and FY 2015. The Panel's goal was to generate the information needed to build collaborations on OA and hypoxia with decision makers across state, regional, tribal, and Federal levels. The IWG-OA has engaged with the West Coast Governor's Association Pacific Coast Collaborative to continue the work of the Panel by building state and Federal partnerships on activities related to OA and hypoxia. In a related effort, NOAA provided funds to the Northwest Straits Commission for an 18-month project to conduct targeted education and outreach on ocean acidification to local elected officials, conservation districts, and conservation groups in Washington State to help them better understand the issue and how they can address it.

Through its Office of Education, NOAA funded "Carbon Networks: Using Local and Regional Datasets, Visualizations and Narratives to Build Educator Capacity," a project executed by The Exploratorium (California), Pacific Science Center (Washington), and Waikiki Aquarium at the University of Hawaii at Manoa. Carbon Networks addresses the disconnect between scientific evidence and the public's understanding of the impacts of OA and carbon dioxide in the atmosphere. The project developed tools to train informal and formal educators in the use of authentic ocean and atmospheric data to create

meaningful place-based education narratives and activities about the impacts of OA and climate change. By connecting local ocean and atmospheric data with that of regional, Pacific, and global systems, Carbon Networks created a new approach to understanding global environmental change by relating it to the local environments that are most relevant to people's lives.

NOAA's Office of Education also funded the Port Townsend Science Society to run a program for Jefferson County, Washington, high school students to explore and study ocean acidification. The Office of Education provided additional support for the Suquamish Tribe to run a project focused on ocean acidification that brings together indigenous communities across the Pacific Ocean basin to share common ideas, values, and traditional ways of knowing by communicating as pen pals. For this latter project, students at various locations conducted research on ocean acidification in their local ecosystems and communicated with their pen pals about how issues related to acidification may impact their respective communities.

NOAA worked with the Seattle Aquarium in Washington to execute testing of seawater pH sensors as part of the Wendy Schmidt Ocean Health X Prize. The month-long tests using seawater from Elliot Bay, Washington, took place in February 2015, and were viewable by visitors to the Seattle Aquarium. This visitor interaction provided an opportunity for education about OA, carbon chemistry, and the technological breakthroughs that are needed to advance OA science.

Theme 7. Data management and integration

IOOS has developed a dedicated website to serve OA chemistry data collected from a variety of observing assets along the United States West Coast, Alaska, and the United States Pacific Islands region. This website facilitates the transfer of observing data from scientists to regional and national stakeholders.

Alaska

Federal ocean acidification activities in Alaska expanded in FY 2014 and 2015, increasing understanding of ocean conditions and the sensitivity of human communities and species to ocean acidification. Notably, researchers developed a vulnerability assessment of Alaska fisheries and fishing communities to ocean acidification, yielding one of the Nation's first and most comprehensive assessments related to ocean acidification. Other developments of note included expansion of the research portfolio on species response to ocean acidification, building of a new experimental laboratory at the Allutiq Pride Shellfish Hatchery, and the first synoptic ocean acidification cruise of the Gulf of Alaska.

Theme 1. Research to understand implications of ocean acidification

NOAA

NOAA maintained shared-user experimental facilities at the Alaska Fisheries Science Center's Kodiak, Alaska, and Newport, Oregon, laboratories to study the response of Alaskan marine species to OA. Research at these facilities was done on northern rock sole, walleye pollock, Pacific cod, speckled sand dab, red king crab, blue king crab, golden king crab, snow crab, and *Primnoa* coral. NOAA and Smithsonian Institution scientists have also characterized the calcium carbonate mineralogy of 62 cold-water corals and a sponge that inhabit Alaskan waters as a way of estimating their sensitivity to OA. Results of these studies demonstrate critical differences among Alaskan fishery species to the effects of OA.

NPS

NPS funded an assessment of the impacts of OA on plankton populations in Glacier Bay, Alaska.

Bureau of Indian Affairs

In FY 2015, the Bureau of Indian Affairs (BIA) gave a grant to the Chugach Regional Resources Commission to build an OA experimental system at the Allutiq Pride Shellfish Hatchery in Seward, Alaska. The Chugach Regional Resources Commission is an inter-tribal fish and wildlife commission with seven member tribes located in the Prince William Sound and lower Cook Inlet created to address environmental and natural resources issues of concern to its members. The system will be used to study the effects of OA on shellfish larvae. Initial research at this laboratory will focus on indigenous shellfish, especially the littleneck clam (*Leucoma staminea*). This clam was once a staple of beach harvests but has nearly disappeared as a local food source in the Prince William Sound and lower Cook Inlet, Alaska.

Theme 2. Monitoring of ocean chemistry and biological impacts

NOAA

NOAA operated two coastal OA moorings in the Gulf of Alaska. In FY 2015, NOAA also completed a synoptic cruise (co-funded by NSF) to characterize the carbon chemistry, primary production, and zooplankton communities of the Gulf of Alaska. The cruise went from Southeast Alaska to Kodiak, Alaska. As also noted above under the United States West Coast section, NOAA maintained underway CO_2 systems on the NOAA ships *Oscar Dyson* and *Bell M. Shimada,* which operate in the California Current Ecosystem, Gulf of Alaska, and Bering Sea. NOAA also completed extensive OA process observing work with multiple assets (e.g., gliders, sail drones, ship of opportunity) in Prince William Sound and Glacier Bay, Alaska.

BIA

In 2015, BIA provided funding to the Chugach Regional Resources Commission to monitor OA in south-central Alaska. The Commission also assists its member tribes in developing their technical capacity to be more meaningfully involved in the environmental and natural resource decisions and regulations that affect their traditional use areas and resources. For the 2-year project, the Commission member tribes, Seldovia Village Tribe, Kasitsna Bay Lab (NOAA), and Kachemak Shellfish Mariculture Association will collect weekly seawater chemistry samples from their docks; the Prince William Sound Science Center will collect seawater chemistry samples on its annual cruise; and the Kachemak Bay National Estuarine Research Reserve will collect seawater chemistry samples during its regular sampling events. This project will expand OA near-shore monitoring beyond Seward, Alaska, and enable Alaska native coastal communities in south-central Alaska to obtain information on OA that is specific and relevant to their local environment.

FWS

The University of Alaska Fairbanks chartered time on the FWS vessel *R/V Tiglax* to conduct carbon chemistry, zooplankton, and other sampling as part of the repeat monitoring of the Seward Line, a long-term observation program in the Gulf of Alaska.

Theme 3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms

NOAA

NOAA supported incorporation of the potential impacts of OA into recruitment and population dynamics models of two Alaska commercial crab species (red king and Tanner crab) and used these population forecasts in fisheries yield and revenue models. This project was based on results from NOAA laboratory species-response studies and yielded information relevant to fisheries management.

NSF

In FY 2014, NSF funded a modeling study to determine what factors are likely to control the carbonate system in waters of the Northern Gulf of Alaska.

NPS

The NPS Alaska Region partnered with Glacier Bay National Park (Alaska) and the University of Alaska Fairbanks to develop a conceptual OA model for the region. The systems-based approach of this conceptual model focuses on trophic linkages between nearshore coastal communities and nearshore coastal dynamics while still considering the physio-chemical characteristics of the environment and the biology found in Alaska's coastal national parks.

Theme 5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems

NOAA

NOAA continued funding a risk assessment of Alaska fisheries to OA; BEOM funding initiated this project in 2013. The study found that important commercial and subsistence fisheries in Alaska are located in regions where enhanced OA will occur, and that coastal human communities in southeast and southwest Alaska face the highest risk from OA.

United States Pacific Islands

Federal ocean acidification activities in the United States Pacific Islands focused on long-term monitoring of coral reef ecosystems and using natural experiments to understand the potential response of reef systems to global change. For the latter, researchers studied the response of coral reefs to high CO_2 conditions at a volcanic CO_2 seep and how the response of coral reef ecosystems to the unusual warming event that took place in 2014 and 2015 may have been influenced by variation in ocean CO_2 conditions. This combination of long-term monitoring and process research in the region yielded powerful datasets to characterize the status of and differences between various coral reef ecosystems in the region and to explain the mechanisms behind regional patterns and trends in reef status.

Theme 1. Research to understand implications of ocean acidification

NOAA

NOAA's activities in the United States Pacific Islands in FY 2014 and FY 2015 focused on coral reef ecosystems. As a part of NOAA's Coral Reef Conservation Program status and trend monitoring, NOAA supported an historical analysis of calcification rates within select coral reef environments, primarily in the Pacific Ocean, through extraction of cores from coral reefs. NOAA Sea Grant funded the University of Hawaii to study coral dissolution under OA, and the tolerance of coral communities to OA, climate change, and altered food regimes using an experimental mesocosm. An expedition to Maug Island in the Commonwealth of the Northern Mariana Islands studied a volcanic CO_2 seep that was used as a natural OA laboratory to elucidate the impacts of high CO_2 on coral reefs.

NSF

NSF supported eight OA-related awards in FY 2014 and three awards in FY 2015 in the United States Pacific Islands. In FY 2014, NSF funded researchers working at the Moorea Coral Reef LTER site in French Polynesia to build on studies of coral species response to OA using both experimental and field approaches. Using coral larvae collected from Hawaiian reefs, NSF-supported researchers are employing multiple cutting edge approaches to examine the matrix formation and calcification in early development stages of stony corals that contain zooxanthellae. Based on preliminary data, the investigators hypothesize that calcification will be possible up to pH levels predicted for 2100 atmospheric CO_2 levels. In FY 2014, NSF also funded a mesocosm study on Hawaiian coral species with the objective of assessing the ability of coral species to respond to OA and other climate variables either with local adaptation or changing their symbiotic associations. A coordinated project is determining the genetic variability of species from the mesocosm study and, in addition, a survey of eight coral species will be undertaken across a gradient of temperature and pCO_2 concentrations.

There were unusually warm temperatures in both the tropical Pacific Ocean and tropical Atlantic Ocean in 2014 and 2015. NSF funded several Grants for Rapid Response Research (RAPID) to examine how coral species responded to combinations of warming water and OA, and whether there were factors that led to increased resilience. A NSF Collaborative Research project is using RAPID funding to determine if Eastern Tropical Pacific coral reefs are becoming more resilient to periodic warming and bleaching events, and whether reefs that differ in their aragonite saturation exposure differ in their ability to recover from warming and bleaching. NSF-funded researchers are also using RAPID funding to examine coral in Kaneohe Bay and Waimanalo Bay, Hawaii, to determine how OA affects coral recovery from bleaching, whether feeding by corals minimizes OA effects, and whether corals in the warmer, lower pH regime of Kaneohe Bay recover more quickly than those in relatively cooler and higher pH Waimanalo Bay. These RAPID awards built on and expanded the ongoing mesocosm studies described above. Another NSF-funded project is examining how ocean warming and OA affect the epidemiology of a marine fungal disease that occurs on red crustose coralline algae. Field observations will be conducted at the Palmyra Atoll, with follow up experimental work at a United States marine laboratory.

Theme 2. Monitoring of ocean chemistry and biological impacts

NOAA

NOAA operated four coral-reef OA moorings off Oahu, Hawaii, and open-ocean OA moorings off the State of Hawaii in the eastern tropical Pacific Ocean and off Japan in the Kuroshio Extension current. NOAA's National Coral Reef Conservation Program monitored the status and trends of the Nation's coral reef ecosystems in the Pacific region, including key chemical and ecological indicators specific to OA. The coral reef observation network has designed three sentinel sites for OA in the Pacific Ocean basin off Oahu, American Samoa, and the Commonwealth of the Northern Mariana Islands. To date, only the Oahu sentinel site has been established. In FY 2014, candidates for the American Samoa site were identified. In FY 2014 and FY 2015, NOAA monitored the progression and impacts of OA at a number of non-sentinel coral reef sites around the Pacific Ocean, including Agrihan, Aguijan, Alamagan, Asunción, Guguan, Rota, Sarigan, Supply Reef, Zealandia seamount, Guam, Maug, Pagan, Saipan, Wake Atoll, and the Marianas.

NSF

NSF supported OA research and monitoring at the Moorea Coral Reef LTER site in French Polynesia. This site focuses on OA as one of the primary disturbances affecting the Moorea reef community.

Theme 3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms

NOAA

NOAA scientists built a sophisticated model of the Guam marine ecosystem and used it to understand how OA and climate change might influence the ecosystem, especially coral reefs.

Theme 4. Technology development and standardization of carbonate chemistry measurements on moorings and autonomous floats

As described under Theme 4 of the United States West Coast section above, in FY 2014 and FY 2015, work on an IOOS and NOAA grant that supports OA sensor development and application targeted to the shellfish industry began across the United States West Coast, Alaska, and Hawaii. In the Pacific Islands region, the project tested a remotely deployable, prototype dissolved inorganic carbon analyzer at a new buoy off of Hawaii.

Theme 6. Education, outreach, and engagement strategy on ocean acidification

NOAA

NOAA Sea Grant funded the University of Guam and the University of Hawaii to increase awareness of climate change and ocean acidification in Guam and throughout the Pacific Islands.

Caribbean

Coral reef ecosystems were the focus of Federal ocean acidification activities in the Caribbean. Coral reefs in this region provide coastal protection, support regional fisheries, and host biodiversity, including species listed under the Endangered Species Act. Information on how ocean acidification is influencing

coral reefs now and will influence them in the future is important for understanding how management systems may need to change to mitigate or adapt to future conditions.

Theme 1. Research to understand implications of ocean acidification

NSF

NSF supported two OA-related awards in FY 2014 and four awards in FY 2015 in the Caribbean region that focused on coral reef systems. One NSF-funded project is conducting laboratory and field studies at a reef site in Bocas del Toro, Panama, using novel immunological approaches to measure critical cellular physiological processes in response to pH, light, and temperature. A collaborative study of coral reefs in the Caribbean and Bermuda is examining how coral reef productivity has responded to changes in ocean mixing over time. The researchers expect that there will be interactions between reef productivity and the coral community response to OA and other changes in climate. Other NSF-funded projects are assessing how metabolism on the Bermuda coral reef is affected by large scale oceanographic processes.

USGS

USGS supported studies on the effects of ocean acidification on coral health and coral reef degradation, as well as monitoring of coralline algae that form crusts of calcium carbonate. Calcification rates measured on field specimens focused on two species of coral that are listed as endangered under the Endangered Species Act. Field studies also examined biogeochemical processes contributing to coral reef erosion. Laboratory studies continued on the effects of lowered pH and higher CO_2 values in seawater on photosynthesis and respiration of different tropical and subtropical benthic organisms, foraminifera, and aragonitic green algae

Theme 2. Monitoring of ocean chemistry and biological impacts

NOAA

NOAA's National Coral Reef Conservation Program monitored the status and trends of the United States Atlantic Ocean coral reef ecosystems, including key chemical and ecological indicators specific to OA. The coral reef observation network has proposed three sentinel sites for OA in the Atlantic Ocean basin. The site established at La Parguera, Puerto Rico, includes an OA mooring. NOAA established a second sentinel site in the Florida Keys (see United States Southeast and Gulf Coast sections above). In FY 2014 and FY 2015, NOAA monitored the progression and impacts of OA at a number of non-sentinel coral reef sites around the Caribbean, including Puerto Rico and the United States Virgin Islands (St. John, St. Thomas, and St. Croix).

NSF

NSF continued to support a Long Term Research in Environmental Biology program that monitors coral reef community dynamics and environmental parameters in St. John, United States Virgin Islands.

Theme 3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms

NOAA

NOAA developed and released maps of aragonite saturation state, alkalinity, dissolved inorganic carbon, pCO_2, temperature, and salinity for the Caribbean and Gulf of Mexico. This work is based on regionally-specific algorithms that use synoptic environmental datasets (e.g., satellite, Hybrid Coordinate Ocean Model) and are verified with observational data.

Theme 4. Technology development and standardization of carbonate chemistry measurements on moorings and autonomous floats

NOAA

NOAA continued to support the development of advanced technologies to quantify net community rates (e.g., calcification, productivity) within coral reef environments at the Atlantic Ocean OA test-beds in Puerto Rico and Florida. The test-bed project investigates the physical and biogeochemical processes controlling temporal variability in OA. Recent work advanced the development of an integrated set of high-precision, *in situ* measurements using state-of-the-art cabled instrumentation that can examine, in real time, the influence of benthic processes on local carbonate chemistry.

Arctic

Federal ocean acidification activities in the Arctic region focused on monitoring and modelling projects that build understanding of ocean carbon chemistry conditions and the biological and physical processes that influence and respond to them. These activities contribute information on this poorly understood ecosystem and its potential future conditions, which is important as Arctic ecosystems and human use of them are changing quickly.

Theme 1. Research to understand implications of ocean acidification

USGS

Following on projects stemming from 2010–2013 Arctic cruises, in FY 2014 and FY 2015 USGS participated in syntheses of baseline data to address ocean acidification in the Canadian Basin of the Arctic Ocean. These syntheses included carbon and isotopic chemistry, and biological/microbial and dissolved organic carbon characterization of the Arctic Ocean. The data collected further the goal of understanding the characteristics of the upper water column to determine the role of sea ice in ocean acidification of the different ocean basins. In FY 2015, USGS participated in a cruise led by the University of Washington, in collaboration with the Bedford Institute of Oceanography, Fisheries, and Oceans, to the Davis Straits to document surface carbon chemistry changes, including ocean acidification, as a result of climate change.

NASA

NASA funded the final data synthesis of the Impacts of Climate on the Eco-Systems and Chemistry of the Arctic Pacific Environment (ICESCAPE) field campaign. The goal of ICESCAPE was to determine the impact of climate change on the biogeochemistry and ecology of the Chukchi and Beaufort Seas. ICESCAPE

utilized an interdisciplinary, cross cutting approach integrating field expeditions, modeling, and satellite remote sensing. The project analyzed observations and research to specifically address ocean acidification and its impacts on the ecology of the Arctic. All ICESCAPE synthesis papers are published in three special issues of *Deep-Sea Research II*.

In addition, NASA supported projects investigating ocean acidification in the Arctic Ocean. One study used biological and bio-optical observations to address the role of calcifying organisms in the Chukchi and Beaufort Seas. This region is expected to undergo fundamental changes associated with melting ice caps, affecting both the biota and the bio-optical properties of the water mass. This project is in the synthesis phase.

NASA also funded a field and modeling project in the Arctic Ocean focused on high-quality, discrete sampling of water column dissolved inorganic carbon and surface, underway pCO_2 and dissolved inorganic carbon observations. The project addresses the impact of natural and anthropogenic factors, such as sea-ice loss, shelf-basin physical dynamics, and net phytoplankton primary production, on the marine inorganic carbon cycle and air-sea CO_2 fluxes. This project is in the synthesis phase, but thus far has produced or contributed to 22 publications, with more research in press. The publications address a variety of topics, including Arctic Ocean surface water pCO_2 in comparison with atmospheric pCO_2, surface seawater pH, aragonite saturation states, carbonate chemistry of ice-melt ponds, and under-ice phytoplankton bloom chemistry. Observations from the project contribute to growing evidence that sea-ice carbonate chemistry is highly variable, and its future contribution to the complex factors that influence the balance of CO_2 sinks and sources and ocean acidification – in an era of rapid warming and sea-ice loss in the Arctic Ocean – is difficult to predict.

Theme 2. Monitoring of ocean chemistry and biological impacts

NOAA

NOAA operated an OA mooring in the North Atlantic off Iceland. In addition, NOAA, BOEM, and Shell Exploration and Production Company funded a Marine Biodiversity Observation Network project in the Chukchi Sea, which included some OA observations.

BOEM

In FY 2015, BOEM published the report "Biogeochemical Assessment of the OCS Arctic Waters: Current Status and Vulnerability to Climate Change" (BOEM 2014-668). This final report summarizes a long-term study that investigated the implications of two climate-change related processes on the carbon biogeochemistry of the North Aleutian Basin and the Chukchi Sea. In 2010, a partnership between BOEM and Fairweather, LLC expanded the already ongoing study to the northeastern Chukchi Sea to consider the response and vulnerability of the wider Alaskan outer continental shelf region to OA.

USGS

USGS ocean acidification projects focused on regional studies of carbon chemistry in the Canada Basin and Davis Strait in the Arctic. These datasets have provided baseline data in areas that have little or no prior carbon chemistry information. These projects have resulted from collaboration with academia and Canadian government agencies on ships of opportunity to understand the effects of climate change in these vulnerable ecosystems.

Theme 3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms

USGS

USGS collaborated with academia to develop saturation state models for the water column in the Arctic based on carbon chemistry, nutrients, and isotopic data in the Canada Basin. These models will inform organismal studies on potential interactions of water column processes.

Theme 6. Education, outreach, and engagement strategy on ocean acidification

USGS

USGS used social media, such as Twitter and Facebook, in coordination with website posts to inform the public about the USGS ocean acidification science projects conducted on Arctic cruises, including the Davis Strait cruise in FY 2015.

SI

As part of a citizen science/demonstration project, the Smithsonian Environmental Research Center teamed up with the non-profit Ocean Research Project for the Greenland Climate Project, a 100-day field campaign aimed at, in part, advancing knowledge of OA in Arctic coastal ocean waters. This continuing collaboration included the installation and operation of a pCO_2 instrument on a private sailboat that cruised from Annapolis, Maryland, to Greenland in the summer of 2015. Upon reaching Greenland, the vessel navigated along the western coast, in and out of fjords, taking and logging pCO_2 measurements continually at 1-minute intervals. The vessel operators also took discrete water samples to measure total alkalinity. The primary goals of the project were to assess the viability of: (1) using a sailboat as a mobile underway sampling platform for the pCO_2 instrument; (2) enlisting capable citizen scientists to determine the feasibility of citizens operating a complex but robust instrument; and (3) conducting a continued long-term sea trial of Smithsonian Environmental Research Center designed and built instrumentation. Preliminary data indicate striking differences in pCO_2 between the open ocean and nearshore coastal waters off Greenland and inside glacier-fed fjords.

Antarctic

Antarctic OA efforts included research projects on the sensitivity of the Antarctic ecosystem's dominant fish group to ocean acidification and temperature change. In addition, monitoring of the ocean carbon chemistry conditions associated with the Long-Term Ecological Research Networks' Palmer Station continued.

Theme 1. Research to understand implications of ocean acidification

NSF

An NSF-funded project is completing work on examining the physiological and genomic response of Notothenioid fishes from the Antarctic and New Zealand in experiments that manipulate CO_2 levels and temperature. The study is characterizing gene expression change and physiological functions and examining the phylogenic relationships of the selected species.

Theme 2. Monitoring of ocean chemistry and biological impacts

NSF

NSF supported observations in coastal waters of the Antarctic Peninsula at the Palmer Antarctic LTER site. Additional ship support is not included in the NSF funding report in the Appendix.

Appendix

Summary of Federally-funded Ocean Acidification Research and Monitoring Activities

Table 1. Summary of all Federally-funded ocean acidification research and monitoring activities[2]

Theme	FY 2014 Budget ($K)	FY 2015 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification	1,306	1,235	Contributing
	15,772	7,524	Primary
	17,078	8,759	Total
2. Monitoring of ocean chemistry and biological impacts	5,425	5,211	Contributing
	4,857	5,643	Primary
	10,282	10,854	Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms	379	370	Contributing
	2,267	1,764	Primary
	2,646	2,134	Total
4. Technology development and standardization of measurements	117	107	Contributing
	2,270	985	Primary
	2,387	1,092	Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems	28	94	Contributing
	78	75	Primary
	106	169	Total
6. Education, outreach, and engagement on ocean acidification	551	482	Contributing
	870	631	Primary
	1,421	1,114	Total
7. Data management and integration	1,196	1,202	Contributing
	718	548	Primary
	1,914	1,750	Total
8. Other ocean acidification research and monitoring activities	0	30	Contributing
	584	1,134	Primary
	584	1,164	Total
Total	9,002	8,731	Total Contributing
	27,416	18,304	Total Primary
	36,417	27,036	Grand Total

[2] USDA funds many programs and projects that indirectly address OA. Federal funding cannot easily be accounted for as directed at OA since USDA has no direct budget lines to address this important issue.

Table 2. Summary of BOEM-funded ocean acidification research and monitoring activities

Theme	FY 2014 Budget ($K)	FY 2015 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification			Contributing
			Primary
			Total
2. Monitoring of ocean chemistry and biological impacts			Contributing
	120	120	Primary
	120	120	Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms			Contributing
			Primary
			Total
4. Technology development and standardization of measurements			Contributing
			Primary
			Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems			Contributing
			Primary
			Total
6. Education, outreach, and engagement on ocean acidification			Contributing
			Primary
			Total
7. Data management and integration			Contributing
			Primary
			Total
8. Other ocean acidification research and monitoring activities			Contributing
			Primary
			Total
Total			Total Contributing
	120	120	Total Primary
	120	120	Grand Total

Table 3. Summary of DOS-funded ocean acidification research and monitoring activities

Theme	FY 2014 Budget ($K)	FY 2015 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification			Contributing
			Primary
			Total
2. Monitoring of ocean chemistry and biological impacts			Contributing
			Primary
			Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms			Contributing
			Primary
			Total
4. Technology development and standardization of measurements			Contributing
			Primary
			Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems			Contributing
			Primary
			Total
6. Education, outreach, and engagement on ocean acidification			Contributing
	747	370	Primary
	747	370	Total
7. Data management and integration			Contributing
			Primary
			Total
8. Other ocean acidification research and monitoring activities			Contributing
			Primary
			Total
Total			Total Contributing
	747	370	Total Primary
	747	370	Grand Total

Table 4. Summary of EPA-funded ocean acidification research and monitoring activities

Theme	FY 2014 Budget ($K)	FY 2015 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification			Contributing
	302	149	Primary
	302	149	Total
2. Monitoring of ocean chemistry and biological impacts	108	158	Contributing
	75	362	Primary
	183	520	Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms			Contributing
	350		Primary
	350		Total
4. Technology development and standardization of measurements			Contributing
			Primary
			Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems			Contributing
	75	75	Primary
	75	75	Total
6. Education, outreach, and engagement on ocean acidification			Contributing
	25	50	Primary
	25	50	Total
7. Data management and integration			Contributing
			Primary
			Total
8. Other ocean acidification research and monitoring activities			Contributing
			Primary
			Total
Total	108	158	Total Contributing
	827	636	Total Primary
	935	794	Grand Total

Table 5. Summary of NASA-funded ocean acidification research and monitoring activities

Theme	FY 2014 Budget ($K)	FY 2015 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification	250	250	Contributing
			Primary
	250	250	Total
2. Monitoring of ocean chemistry and biological impacts			Contributing
			Primary
			Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms	267	261	Contributing
			Primary
	267	261	Total
4. Technology development and standardization of measurements			Contributing
			Primary
			Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems			Contributing
			Primary
			Total
6. Education, outreach, and engagement on ocean acidification			Contributing
			Primary
			Total
7. Data management and integration			Contributing
			Primary
			Total
8. Other ocean acidification research and monitoring activities			Contributing
			Primary
			Total
Total	517	511	Total Contributing
			Total Primary
	517	511	Grand Total

Table 6. Summary of NOAA-funded ocean acidification research and monitoring activities

Theme	FY 2014 Budget ($K)	FY 2015 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification	1,056	985	Contributing
	1,941	2,055	Primary
	2,997	3,040	Total
2. Monitoring of ocean chemistry and biological impacts	2,652	2,553	Contributing
	3,441	3,919	Primary
	6,093	6,472	Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms	37	37	Contributing
	1,415	1,750	Primary
	1,452	1,787	Total
4. Technology development and standardization of measurements	37	37	Contributing
	559	361	Primary
	596	398	Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems	28	94	Contributing
	3		Primary
	31	94	Total
6. Education, outreach, and engagement on ocean acidification	65	50	Contributing
	74	73	Primary
	139	123	Total
7. Data management and integration	446	452	Contributing
	693	511	Primary
	1,139	963	Total
8. Other ocean acidification research and monitoring activities			Contributing
	559	1,110	Primary
	559	1,110	Total
Total	4,321	4,208	Total Contributing
	8,685	9,779	Total Primary
	13,006	13,987	Grand Total

Table 7. Summary of NPS-funded ocean acidification research and monitoring activities

Theme	FY 2014 Budget ($K)	FY 2015 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification			Contributing
		125	Primary
		125	Total
2. Monitoring of ocean chemistry and biological impacts			Contributing
	106	181	Primary
	106	181	Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms			Contributing
		14	Primary
		14	Total
4. Technology development and standardization of measurements			Contributing
			Primary
			Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems			Contributing
			Primary
			Total
6. Education, outreach, and engagement on ocean acidification			Contributing
			Primary
			Total
7. Data management and integration			Contributing
			Primary
			Total
8. Other ocean acidification research and monitoring activities			Contributing
			Primary
			Total
Total			Total Contributing
	106	320	Total Primary
	106	320	Grand Total

Table 8. Summary of NSF-funded ocean acidification research and monitoring activities

Theme	FY 2014 Budget ($K)	FY 2015 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification			Contributing
	13,309	4,977	Primary
	13,309	4,977	Total
2. Monitoring of ocean chemistry and biological impacts	2,665	2,500	Contributing
			Primary
	2,665	2,500	Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms			Contributing
	502		Primary
	502		Total
4. Technology development and standardization of measurements			Contributing
	1,571	494	Primary
	1,571	494	Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems			Contributing
			Primary
			Total
6. Education, outreach, and engagement on ocean acidification	486	432	Contributing
		118	Primary
	486	551	Total
7. Data management and integration	750	750	Contributing
			Primary
	750	750	Total
8. Other ocean acidification research and monitoring activities		30	Contributing
			Primary
		30	Total
Total	3,901	3,712	Total Contributing
	15,382	5,589	Total Primary
	19,283	9,302	Grand Total

Table 9. Summary of SI-funded ocean acidification research and monitoring activities. Although the Smithsonian Institution did receive Federal appropriations in FY 2014 and FY 2015, none was designated directly for support of OA research, monitoring, technology development, or other activities. Unlike many other Federal agencies[3], the Smithsonian Institution is not a granting/funding agency by which Federally-appropriated agency monies are distributed externally via proposal competitions. Instead, SI scientists routinely collaborate with investigators inside and outside the Institution and compete for grants and research contracts in much the same way academic scientists do. Scientists at the Smithsonian Institution can be either Federal employees or non-Federal employees whose salaries rely on grants, contracts, and sometimes philanthropic support. Regardless of Federal or non-Federal status, SI employee salary support, commensurate with time contributed, is captured as a portion of Smithsonian Institution contributions to OA research and monitoring activities in FY 2014 and FY 2015. Likewise, funding acquired through external grants and contracts, as well as any internally sourced funding, is accounted for in this report.

Theme	FY 2014 Budget ($K)	FY 2015 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification			Contributing
	195	218	Primary
	195	218	Total
2. Monitoring of ocean chemistry and biological impacts			Contributing
	34	34	Primary
	34	34	Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms			Contributing
			Primary
			Total
4. Technology development and standardization of measurements			Contributing
			Primary
			Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems			Contributing
			Primary
			Total
6. Education, outreach, and engagement on ocean acidification			Contributing

[3] The Smithsonian Institution is a trust instrumentality of the United States, lawfully created by the United States Congress in 1846 to exercise the authority of the United States in carrying out the responsibilities Congress undertook when it accepted the bequest of James Smithson "to found at Washington, under the name of the Smithsonian Institution, an establishment for the increase and diffusion of knowledge among men." The Smithsonian is recognized by the Internal Revenue Service as a 501(c)(3) tax-exempt educational organization. Unlike most Federal agencies, the Smithsonian is authorized to accept gifts and to generate revenue outside of the Federal appropriations process. Thus, the Smithsonian complies with Internal Revenue Service regulations and practices applicable to tax-exempt organizations, which it implements through policies and practices, including directives on Philanthropic Financial Support and Use of Facilities for Special Events. The Smithsonian files an Internal Revenue Service Form 990, the IRS information return for tax-exempt organizations.

		5	Primary
		5	Total
7. Data management and integration			Contributing
		13	Primary
		13	Total
8. Other ocean acidification research and monitoring activities			Contributing
			Primary
			Total
Total	0	0	Total Contributing
	229	270	Total Primary
	229	270	Grand Total

Table 10. Summary of FWS-funded ocean acidification research and monitoring activities

Theme	FY 2014 Budget ($K)	FY 2015 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification			Contributing
			Primary
			Total
2. Monitoring of ocean chemistry and biological impacts			Contributing
			Primary
			Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms			Contributing
			Primary
			Total
4. Technology development and standardization of measurements			Contributing
			Primary
			Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems			Contributing
			Primary
			Total
6. Education, outreach, and engagement on ocean acidification			Contributing
	8.5		Primary
	8.5		Total
7. Data management and integration			Contributing
			Primary
			Total
8. Other ocean acidification research and monitoring activities			Contributing
			Primary
			Total
Total			Total Contributing
	8.5		Total Primary
	8.5		Grand Total

Table 11. Summary of USGS-funded ocean acidification research and monitoring activities

Theme	FY 2014 Budget ($K)	FY 2015 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification			Contributing
	25	0	Primary
	25	0	Total
2. Monitoring of ocean chemistry and biological impacts			Contributing
	1,081	1,027	Primary
	1,081	1,027	Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms	75	72	Contributing
			Primary
	75	72	Total
4. Technology development and standardization of measurements	80	70	Contributing
	140	130	Primary
	220	200	Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems			Contributing
			Primary
			Total
6. Education, outreach, and engagement on ocean acidification			Contributing
	15	15	Primary
	15	15	Total
7. Data management and integration			Contributing
	25	24	Primary
	25	24	Total
8. Other ocean acidification research and monitoring activities			Contributing
	25	24	Primary
	25	24	Total
Total	155	142	Total Contributing
	1,311	1,220	Total Primary
	1,466	1,362	Grand Total

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Abbreviations

AOML	Atlantic Oceanographic and Meteorological Laboratory
BIA	Bureau of Indian Affairs
BOEM	Bureau of Ocean Energy Management
CalCOFI	California Cooperative Oceanic Fisheries Investigation
CCAN	California Current Acidification Network
CLIVAR	Climate and Ocean: Variability, Predictability, and Change
CO_2	Carbon Dioxide
CORAL	Coral Reef Airborne Laboratory
EPA	Environmental Protection Agency
FOARAM	Federal Ocean Acidification Research and Monitoring Act of 2009 (P.L. 111-11, Subtitle D)
FWS	United States Fish and Wildlife Service
FY	fiscal year
GFDL	National Oceanic and Atmospheric Administration Geophysics Fluid Dynamics Laboratory
ICESCAPE	Impacts of Climate on the Eco-Systems and Chemistry of the Arctic Pacific Environment
IOOS	United States Integrated Ocean Observing System
IWG-OA	Interagency Working Group on Ocean Acidification
LTER	Long-Term Ecological Research
M	million
NASA	National Aeronautics and Space Administration
NCEI	National Centers for Environmental Information
NECAN	Northeast Coastal Acidification Network
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
NSF	National Science Foundation
NSTC	National Science and Technology Council
OA	ocean acidification

OADS	Ocean Acidification Data Stewardship Program
OSTP	Office of Science and Technology Policy
pCO_2	partial pressure of carbon dioxide
PACE	Pre-Aerosol, Cloud, and ocean Ecosystem
ppm	Parts per million
RAPID	National Science Foundation Grants for Rapid Response Research
SOCAN	Southeast Ocean and Coastal Acidification Network
STAR	Science To Achieve Results
State	United States Department of State
STEM	Science, Technology, Engineering, and Mathematics
Strategic Plan	*Strategic Plan for Federal Research and Monitoring of Ocean Acidification*
USDA	United States Department of Agriculture
USGS	United States Geological Survey