FIFTH REPORT ON FEDERALLY FUNDED OCEAN ACIDIFICATION RESEARCH AND MONITORING ACTIVITIES: FISCAL YEARS 2016 AND 2017

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List of Acronyms

BIA	Bureau of Indian Affairs
BOEM	Bureau of Ocean Energy Management
CO_2	Carbon Dioxide
CORAL	Coral Reef Airborne Laboratory
CRCP	Coral Reef Conservation Program
DOS	United States Department of State
EPA	Environmental Protection Agency
FOARAM	Federal Ocean Acidification Research and Monitoring Act of 2009
FWS	United States Fish and Wildlife Service
FY	Fiscal Year
GOA-ON	Global Ocean Acidification Observing Network
ICESCAPE	Impacts of Climate on the Eco-Systems and Chemistry of the Arctic Pacific Environment
IOC	Intergovernmental Oceanographic Commission
IOOS	United States Integrated Ocean Observing System
IWG-OA	Interagency Working Group on Ocean Acidification
LTER	Long-Term Ecological Research
M	million
MACAN	Mid-Atlantic Ocean Acidification Network
MarineGEO	Marine Global Earth Observatory
NASA	National Aeronautics and Space Administration
NECAN	Northeast Coastal Acidification Network
NEPA	National Environmental Policy Act
NMSF	National Marine Sanctuary Foundation
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
NSF	National Science Foundation
NSTC	National Science and Technology Council
OA	ocean acidification
OOI	Ocean Observatories Initiative
OSTP	Office of Science and Technology Policy
PACE	Pre-Aerosol, Cloud, and ocean Ecosystem
pCO2	partial pressure of carbon dioxide
ppm	Parts per million
SOCAN	Southeast Ocean and Coastal Acidification Network
STAR	Science To Achieve Results
Strategic Plan	Strategic Plan for Federal Research and Monitoring of Ocean Acidification
UNOLS	University-National Oceanographic Laboratory System
USDA	United States Department of Agriculture
USGS	United States Geological Survey

Introduction

Ocean acidification, the reduction in ocean pH caused primarily by uptake of anthropogenically released carbon dioxide (CO_2) from the atmosphere, will likely cause serious impacts on marine ecosystems and the services those systems provide to society. This document summarizes Federal activities on ocean acidification (OA) in Fiscal Years (FY) 2016 and 2017. It is organized into sections corresponding to the nine geographic regions in which Federal agencies studied OA in FY 2016 and FY 2017, as well as sections devoted to national and global efforts. The content within each section 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 the Federal agency. Some regions did not host activities for every thematic area. An additional category called "Other 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' OA research and monitoring activities. Expenditures are classified as having either a primary focus on OA or being contributing activities that were designed for other purposes but clearly provide information useful for understanding OA. In FY 2016, Federal agencies provided approximately $23 million (M) toward activities with a primary focus on OA and an additional $19M for contributing activities. In FY 2017, Federal funding was approximately $22M for primary activities and $25M for contributing activities. This investment has created and provided continued support for jobs in sectors related to science, engineering, and technology and has done much to build the resiliency of coastal communities and related economies to the many threats from OA.

Global

Ocean acidification is a global phenomenon however few research projects 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.

Theme 1. Research to understand implications of ocean acidification

NASA continued funding satellite-based research focusing on ocean biology and biogeochemistry, mainly using ocean color satellites. NASA also funded efforts to reduce uncertainty when measuring phytoplankton chlorophyll and many other ocean biology, ecology, and biogeochemistry data products in the ocean.

NSF supported three summer fellowships for U.S. researchers to conduct studies related to OA at foreign laboratories. These projects included a study to test the ability of corals to calcify under current and future climate conditions and a research initiation grant at Hampton College to examine how OA affects visual and auditory abilities of important species from several different ocean regions. NSF also funded projects that focused on reconstructing and understanding variability in ocean pH and alkalinity over timescales longer than the instrumental record and developing the geochemical tools required for the reconstructions, such as boron isotopes.

NSF continued support of a project to examine paleo records during the Cenomanian Turonian Boundary period of climate warming and inform modelers about the probable associated changes in the pelagic food web structure. NSF supported three awards for a collaborative project to examine paleo records from the Eocene Thermal Maximum-2 climate event and document the duration of pH and temperature recovery

from this event.

USGS continued 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.

Theme 2. Monitoring of ocean chemistry and biological impacts

NOAA and NSF supported the collection of open-ocean, surface-to-bottom carbon data as part of the international Global Ocean Ship-based Hydrographic Investigation Program (GO-SHIP). Surface CO_2 measurements from this and other programs are collated in the Surface Ocean CO_2 Atlas. As of June 2017, the Atlas contained 21.5 M observations of surface ocean partial pressure CO_2 collected between 1957 to 2017. 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 OA.

NASA continued to support development of the Plankton, Aerosol, Cloud, and ocean Ecosystem (PACE) satellite mission. The PACE mission addressed OA by understanding and quantifying ocean biogeochemical cycling, and ecosystem function due to natural and anthropogenic forcings from environmental/climate variability and change; extending key Earth system data records on global ocean ecology and biogeochemistry; and enabling carbon monitoring and management.

In FY 2015, NASA funded six Earth Venture Suborbital-2 investigations, including the COral Reef Airborne Laboratory (CORAL) project. CORAL is designed to determine the functional link between coral reef condition and the biogeophysical (i.e., biological and environmental) conditions that impact coral reef ecosystems. This project will provide more detailed data needed for a better understanding of ecosystem function and the economic and ecological value of coral-reefs.

NOAA conducted OA cruises within the United States coastal waters and global oceans and supported 19 OA buoys along the coasts of the United States and in the open ocean, some of which included collaboration and co-funding with International partners. OA buoys locations include in the North Pacific, 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. NOAA's Ocean Observing and Monitoring Division operated a number of other moorings that address OA by collecting pCO_2 data only. NOAA operated the largest ship-of-opportunity effort for surface CO_2 observations in the world, collecting underway pCO_2 data from a number of commercial and other vessels in coastal and international waters.

NSF provided support for ongoing continuous plankton recorder surveys in the North Atlantic Ocean. NSF also supported mid-ocean time series stations in both the Atlantic and Pacific Oceans, the Bermuda Atlantic and Hawaii Ocean time series. Observations at these sites included measurements of ocean primary productivity and changes in the ocean biota, nutrients, pH, and carbonate chemistry. The University-National Oceanographic Laboratory System (UNOLS) vessels provided significant ship support for site sampling. NSF also supported CO_2 measurements as part of the United States Climate and Ocean: Variability, Predictability and Change repeat hydrography survey program. The NSF Ocean Observatories Initiative (OOI) provided 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. NSF funded a project to combine research on the feedback between the cycling of major ocean cations in seawater and the global carbon cycling.

NSF supported a study of carbon cycling processes in carbonate-dominated benthic environments in Bermuda. The study measures flux rates of O_2 and H^+ in coral reef, sand, and seagrass ecosystems to determine rates of net community production and net community calcification.

SI incorporated pCO_2 measurements at several of its marine science directorates and is in the process of incorporating total alkalinity measurements. These monitoring efforts at 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 are part of a larger Smithsonian coastal ocean observing initiative, the Marine Global Earth Observatory (MarineGEO), directed by the Tennenbaum Marine Observatories Network.

USGS continued operation of their Carbon Analytical Laboratory and supported discrete carbon system measurements coordinated with coral growth studies in the Florida Keys, sediment analyses in the Gulf of Mexico, and autonomous carbon system analyses in Tampa Bay.

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

NOAA's Geophysical Fluid Dynamics Laboratory contribution to OA research focused on three areas: (1) sensitivity studies and analysis of historical and projected OA in coupled climate-carbon Earth System Models to assess multiple stressors, including OA, on ocean ecosystems and biogeochemistry; (2) prototyping models at high resolution; and (3) development of the next generation coupled model for participation in the 6th Coupled Model Intercomparison Project, which includes historical and future projections with OA. NOAA Earth System Model experiments included uncertainty quantification of future ocean carbon uptake and attribution of when OA impacts can be detected from decadal alkalinity measurements.

NOAA published papers on the global distribution of calcium carbonate saturation state and pH. The latter paper quantifies the controlling mechanisms of pH from temperature, pressure, biological activities, and calcium carbonate dissolution.

NSF supported two awards for a collaborative project to develop a thermodynamic chemical speciation model for oceans, seas, and estuaries.

SI worked to develop a model that relates high-frequency surface water pCO_2 measurements to a variety other water quality parameters. Using growing MarineGEO data sets, the model will allow for comparisons across latitudes and geographically distributed coastal ecosystems.

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

NOAA Pacific Marine Environmental Laboratory worked with engineers at Saildrone, Inc. to deploy a carbon system on a Saildrone, a wind- and solar-powered, autonomous surface vehicles that can collect a variety of oceanographic measurements. The Saildrones were tested in the Arctic, Gulf of Mexico, and equatorial Pacific Ocean. Two Saildrones were deployed for 6 months in the eastern tropical Pacific. NOAA worked on developing a coastal density glider that can profile shallow water columns for 3 months and a LIDAR system that would attach to a coastal density glider for monitoring the health of fragile coral ecosystems and fisheries in Southeast region. NOAA also worked on developing a cost-effective, sub-surface automated sampler for field-based OA research in shallow marine ecosystems.

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 worked with the winners of the Wendy Schmidt Ocean Health X Prize competition to assess the new, low-cost iSAMI system that won the X Prize for an affordable and accurate pH sensor at the surface and at depth.

NSF continued to support the production of CO_2 reference standards for dissolved inorganic carbon and total alkalinity. It also supported six technology projects focused on OA research, including developing a profiling glider pH sensor to make high-resolution measurements in coastal waters and supporting a scientific review of autonomous and drifting platforms and sensors, a study of CO_2 hydration in seawater, and the development of a high-performance, mass-spectrometry-enabled method for assessing hypoxia and pH stress in marine species.

USGS continued collaboration with academics on developing an inexpensive pH sensor with precision of 0.01 pH units for use in coastal, riverine, and estuarine systems, and designed for use in citizen-science efforts. USGS developed additional collaborative activities with academics for development and deployment of autonomous systems for measuring carbon system parameters in Tampa Bay and the Gulf of Mexico.

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

NOAA, NSF, and NASA contributed funds to help host the *Oceans in a High CO_2 World* conference in Hobart, Tasmania in spring 2016. Over 350 scientists from around the world attended the conference. DOS funded a public-private partnership with The Ocean Foundation to expand OA monitoring through two regional training workshops (Fiji in 2017, Colombia in 2019), equipment kits for ocean monitoring kit, and ongoing mentoring. This partnership is funded with DOS FY 2015 money, with a project period from September 2016 through August 2019. Funded activities include blue carbon restoration projects and the monitoring of the effects of restoration on local ocean chemistry. The NOAA OA Program office did much of the logistical support for the DOS-funded OA training course in Fiji in September 2017.

DOS funded and administered a 2016 workshop entitled "The Pathways to Adaptation: Ocean Acidification in the Arctic" in Helsinki, Finland, as part of the U.S. Arctic Council Chairmanship, with support from NOAA, the Natural Resources Defense Council, and the Finnish Meteorological Institute. The Arctic Council's Arctic Monitoring and Assessment Programme workshop convened 40 scientists, economists, and stakeholders from all eight Arctic countries to forge a path to OA adaptation in the Arctic.

OA remained a key issue at the third Our Ocean conference hosted by DOS in Washington, DC, in September 2016. At the 2016 and 2017 Our Ocean conferences, the United States announced contributions to support the OA International Coordination Center.

The "Ocean pH Research Integration and Collaboration in Africa" (ApHRICA) program, a public-private partnership of government, civil society, and private stakeholders announced by the United States at the 2015 Our Ocean conference, continued to make progress. Nineteen scientists from six countries attended a training workshop and receive ongoing mentorship as part of the Global Ocean Acidification Observing Network (GOA-ON) Pier-2-Peer Network. The DOS and the Swedish International Development Agency co-sponsored a follow-up training for the four scientists who were selected to receive a kit of equipment and a stipend to monitor OA in their countries' coastal waters. ApHRICA has leveraged more than $1 million in additional funding from multiple sources to expand the program's capacity building activities.

OA has become an integral part of the training that U.S. 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 U.S. agencies on this topic, helping officers become more effective science diplomats.

NOAA has been instrumental in the growth of the GOA-ON, with the NOAA OA Program Director serving as co-chair of the network. The third GOA-ON workshop was hosted in 2016, and focused on developing protocols for OA observing systems, discussing where OA monitoring should take place, and outlining essential ocean variables for GOA-ON. GOA-ON has over 370 members representing 67 nations. Pier-2-Peer, a new GOA-ON mentorship program run by the NOAA Ocean Acidification Program, was launched in May 2016. Pier-2-Peer fosters a sense of community and inclusion within the GOA-ON membership by providing interested members with one-to-one, cross-cultural learning opportunities with some enhanced access to resources. Over 50 pairs are matched in the program.

NOAA and academic partners worked closely with the U.N. Intergovernmental Oceanographic Commission's (IOC) Western Pacific Subcommission to provide technical assistance and develop regional capacity across the Western Pacific. This effort works to establish an interdisciplinary regional OA observing network for coral reef ecosystems adopted from related efforts across the U.S. Pacific Islands. During a series of four training workshops from FY 2015 through FY 2017, countries across Southeast Asia (including Bangladesh, China, Indonesia, Malaysia, Philippines, Thailand, and Vietnam) identified over 21 integrated pilot sites and initiated efforts to monitor the ecological impacts of OA using regionally-agreed standard operating procedures adapted from those used by NOAA.

NOAA was active in communicating about OA science, giving a number of talks at international conferences including the UN Open-ended Informal Consultative Process on Oceans and the Law of the Sea, UN Oceans Conference, 2016 Conference of the Parties, and Global Ocean Observing System (GOOS) 8th Regional Alliance meeting. NOAA worked with Fisheries and Oceans Canada in FY 2017 to develop a bilateral agreement on OA for working together on OA.

NSF supported international carbon cycling planning and coordinating activities through the Scientific Committee on Oceanic Research. NSF also contributed to the Gordon Research Conferences program for a symposium on Ocean Global Change and a conference on organism physiological and behavioral changes to ocean climate change.

Theme 7. Data management and integration

Data management activities for the ocean component of the Carbon Dioxide Information Analysis Center at Oak Ridge National Laboratory ceased in December, 2016, putting at risk data from almost 25 years of ocean carbon observations and jeopardizing availability of current and future data. The Ocean Carbon Data System launched in August 2017, giving the NOAA National Centers for Environmental Information the responsibility of hosting and providing access for ocean carbon data collected from around the world, as previously performed by Carbon Dioxide Information Analysis Center. The new data system organizes, quality assures, documents, archives, and disseminates ocean carbon data including measurements from research ships, commercial ships, and moorings collected as part of US and International ocean carbon observing programs. This effort is jointly funded by NASA and NOAA.

The NOAA National Centers for Environmental Information serve as the OA data management focal point for NOAA under the OA Data Stewardship project. This project provides dedicated long-term archival, online data discovery and access for a diverse range of OA-related data sets, including those from multi-disciplinary field observations, laboratory experiments, model outputs, and socioeconomic studies for NOAA and its partners. The Stewardship project developed a metadata standard that is capable of accommodating OA data from research cruises, moorings, models, and laboratory or mesocosm studies to

understand species responses to OA. Over the last three years, the Stewardship project has been working on an advanced submission interface.

GOA-ON created and enhanced the capabilities of its data portal with a global map of OA measurements, which includes international data synthesis products.

The Smithsonian Environmental Research Center scientists and information technology experts designed and developed 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 and making these data publicly available via downloading.

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 are considered "national" in this report, even though the entire portfolio builds knowledge useful for national application.

Theme 1. Research to understand implications of ocean acidification

EPA's Safe and Sustainable Water Resources Program continued research on the relationship between nutrient-related water quality processes and the carbonate system in coastal waters (described in the regional sections). This effort assists states and regions in addressing nutrient pollution and acidification by developing and providing scientific information to inform nutrient related policy.

USDA's National Atmospheric Deposition Program funded research and monitoring efforts that targeted the atmospheric deposition of anthropogenically produced nitrogen, sulfur, and other compounds. These data can be used to extrapolate deposition of nitrogen and sulfur oxides into the ocean. USDA has several programs aimed at the reduction of nutrients going into the Nation's waterways, which can cause coastal hypoxia and acidification. USDA programs also focused on carbon sequestration, reduced emissions of greenhouse gasses, and the production of agriculture-based biofuels.

Theme 2. Monitoring of ocean chemistry and biological impacts

EPA provided technical assistance for pH and pCO_2 monitoring to eight National Estuary Programs: Barnegat Bay Partnership, Casco Bay Estuary Partnership, Coastal Bend Bays and Estuaries Program, Long Island Sound Study, Massachusetts Bays National Estuary Program, San Francisco Estuary Partnership, Santa Monica Bay Restoration Commission, and Tampa Bay Estuary Program.

The NOAA's OA Program grew the National Ocean Acidification Observation Network, which utilizes 19 stationary buoy platforms, hydrographic research cruises, and vessels equipped with autonomous sensors to quantify carbonate chemistry dynamics across a range of environments. Regional, hydrographic, coastal cruises cover the following US regions on an approximately 4-year cycle: Gulf of Alaska, California Current, East Coast (Nova Scotia to Florida), and the Gulf of Mexico. All of the cruises involve international partners and data collection in neighboring exclusive economic zones. NOAA's National Coral Reef Monitoring Program supported long-term monitoring of biological, physical, and socioeconomic indicators throughout the U.S. Pacific, Atlantic, Gulf of Mexico, and Caribbean coral reef areas.

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

EPA developed guidelines for measuring changes in seawater pH and associated carbonate chemistry in coastal environments of the Eastern United States. These guidelines target various audiences with differing areas of expertise, from shellfish growers to citizen monitoring groups and advanced chemistry laboratories.

NOAA's Small Business Innovation Research Program funded Polestar Technologies, Inc. and Sunburst Sensors to develop autonomous instruments to measure carbonate ions in saline waters. The program also funded a second year of work on C.A. Goudey & Associates' project to engineer structures for offshore macroalgae farming, which could potentially reduce the rate of OA in local areas. NOAA funded the University of New Hampshire to develop a commercial total alkalinity sensor.

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. NOAA funded University of Delaware to standardize how pH is measured for long-term monitoring from coastal waters to open ocean.

USGS designed and developed a component packaging system for deployment of the USGS Ocean Carbon System on moorings. This system, originally designed for seafloor deployment, allows for mid- to surface-water column measurement of OA parameters.

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

EPA is working to quantify the potential influence of OA on ecosystem services, completing an assessment of the economic impacts of OA on shellfish in two locations (Puget Sound, WA; Gulf of Maine).

NOAA funded three regional OA vulnerability assessments in order to provide actionable information for marine resource decision makers. The assessments focused on coupled social-ecological vulnerability to OA of four tribal communities along the coast of the Olympic Peninsula (University of Washington), assessing the oceanographic sources of OA and resultant vulnerabilities of communities along the Northeast coast (University of Maine), and conducting a vulnerability assessment of user groups dependent on four economically-important shellfish species in the Pacific Northwest (Oregon State University).

NPS conducted a literature review of the socioeconomic effects of OA. A methodology was developed for a unit-specific case study to assist NPS in understanding the potential order-of-magnitude of OA's socioeconomic impacts.

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

The IWG-OA launched a collaboration website called the OA Information Exchange, as called for in the FOARAM Act of 2009. The website serves all stakeholders interested in OA and allows users to share resources, access up-to-date information, and interact with others across disciplines and geographic regions. The Northeast Regional Association of Coastal Ocean Observing Systems operates the OA Information Exchange with funding from NOAA and BOEM.

The IWG-OA participated in the 2016 Capitol Hill Oceans Week, hosted two webinars on measuring OA monitoring, and held listening sessions with non-governmental organization stakeholders and shellfish growers. The IWG-OA was also tasked with OA-related activities in the National Ocean Council's 2016 priorities, tracked implementation of the *Strategic Plan for Federal Research and Monitoring of Ocean Acidification*, and estimated the costs of implementing the entire *Strategic Plan,* presenting the estimates to the co-chairs of the Subcommittee on Ocean Science and Technology and Office of Management and Budget.

NSF and NASA provided 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 4th United States Ocean Acidification Principal Investigator Meeting held in February 2018.

EPA published a public-facing website for ocean and coastal acidification which includes basic information, causes and effects of OA, EPA activities, and what the public can do to assist these efforts. EPA also initiated an analysis of challenges in acidification outreach and communication, and drafted an internal assessment of appropriate channels and next steps for acidification communication.

NOAA staff throughout the country engaged in a variety of OA-related education, outreach, and engagement activities in addition to a number of NOAA website and social media accounts highlighting OA. NOAA also trained many undergraduate students in OA research methodologies through a variety of internship programs. NOAA offices developed summaries and explanations of OA and related science efforts for communication platforms such as NOAA's "Science on a Sphere". NOAA continued the Sharing OA Resources for Communicators and Educators webinar series, which has reached over 1,450 participants to date.

In response to an OA education needs assessment in FY 2016, the NOAA OA Program created an OA Education MiniGrant program to fill high priority gaps identified. The awardees are working to develop OA curricula, educational multi-media tools, and citizen-science programs on both the West and Northeast coasts of the US. NOAA hosted OA workshops at the 2016 National Marine Educators Association Conference, CommOcean2016 International Marine Science Communication Conference, and 2017 International Council for the Seas Annual Science Conference meeting.

NOAA contributed to reports such as the Second State of the Carbon Cycle Report and National Climate Assessment. NOAA also held a workshop on the development of predictive carbon cycle science. The workshop generated a roadmap on how to further develop and enhance capacity to predict future carbon dynamics in North America and informed the Second State of the Carbon Cycle Report.

NPS developed an article that details the basics of OA, Ocean Acidification 101, as part of the Parks 101 campaign.

NSF contributed to OA outreach by supporting the National Academy of Sciences, Ocean Studies Board activities. 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.

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. USGS contributed to production of an educational film on OA by the Ocean Conservancy. Through engagement with the Southeast Ocean and Coastal Acidification Network and as a member of the Ocean

Acidification Information Exchange steering committee, USGS developed education, outreach and engagement strategies for stakeholders and the public.

Theme 7. Data management and integration

The Biological and Chemical Oceanography Data Management Office (BCO-DMO) 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. BCO-DMO transfers oceanographic data to NOAA National Centers for Environmental Information for permanent archival.

Theme 8. Other research and monitoring activities

EPA supported an Oak Ridge Institute for Science and Education fellow in a project researching the potential to address OA through the Clean Water Act.

FWS manages significant marine areas within National Wildlife Refuge System and the marine national monuments. A large portion of the FWS contribution to OA reduction is the management policies that contribute to locally healthy ecosystems, which offer improved resilience to the effects of OA. Collection of data related to OA in the Refuge System is done by Federal, state, or university partners.

NOAA supports the NOAA OA Program Office as directed by the FOARAM Act of 2009. The OA Program coordinates OA-related research and monitoring across NOAA and directly supports OA efforts in NOAA laboratories. The OA Program also oversees a competitive, merit-based process for awarding grants that explore the effects of OA on ecosystems and the socioeconomic impacts of increased OA.

USDA-funded programs address OA indirectly through programs addressing climate change and run-off of excess nutrients into the Nation's waterways. USDA also funds research, education, and extension activities and projects that are directly related to OA, 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.

United States Northeast

Theme 1. Research to understand implications of ocean acidification

EPA continued its work on biological responses to OA and developed a system that simulates the co-occurring processes of nutrient-driven hypoxia and acidification in coastal environments. EPA completed a collaboration with the University of Rhode Island studying plankton community responses to acidification. EPA also continued its study of coastal acidification impacts on shellfish in Narragansett Bay, RI. This work is closely related to EPA's continuing collaboration (via in-kind support) with Stony Brook University (NY) on a NOAA-funded study of OA effects on resource shellfish populations. EPA also conducted research to predict responses of estuarine production and carbonate chemistry to nutrient loading using stable carbon isotopes. Through its Science To Achieve Results (STAR) program, EPA continued funding a study at the University of Rhode Island focusing on the effects of elevated CO_2 and nutrients on marine communities and trophic interactions.

NOAA maintains shared-user experimental facilities to study species response to OA at the Northeast Fisheries Science Center's Highlands, NJ, and Milford, CT, laboratories. NOAA conducted OA research on winter flounder, Atlantic silverside, and blue mussels. NOAA Sea Grant funded the following: Stony

Brook University to study the impacts of climate change and OA on economically important shellfish and identify effective mitigation and adaptation measures; Woods Hole Oceanographic Institution (MA) to quantify the contribution of wastewater effluent to coastal acidification and develop sensors for measuring OA; Northeastern University (MA) to investigate the effects of OA on shell properties in commercially important New England mollusks; and University of Massachusetts to study the impact of multiple climate stressors on American lobsters. NOAA's OA Program and the Northeast Sea Grant Programs jointly funded new research on how OA may affect important species in the Northeast region, following research needs identified by the Northeast Coastal Acidification Network. The joint effort funded Stony Brook University to study potential adaptation of blue mussels to increasing OA and identify molecular markers associated with resilience to OA in the eastern oyster, hard clam, and blue mussel; University of Connecticut to study the growth and survival of the key forage fish species Northern sand lance to multiple changes in ocean conditions including OA; and University of Maine to study how young lobsters will respond to different temperature and OA conditions that mimic those expected in the next century in the Northeast. Through its Saltonstall-Kennedy grant program, NOAA funded the Bigelow Laboratory for Ocean Sciences to study how kelp affects OA conditions in Maine.

NPS supported Stony Brook University to quantify the temporal and spatial dynamics of hypoxia, acidification, calcium carbonate saturation state, and bivalve growth in Jamaica Bay, NY and to include pH monitoring in water quality measurements.

NSF funded Northeastern University to enhance their capacity for ecological and evolutionary research and for conducting research focused on OA and other environmental stressors. NSF supported a study of Long Island Sound to determine how two species of copepods respond to different temperature and CO_2 conditions in order to assess adaptation capacity and explore epigenetic and genetic mechanisms that might be involved in response. NSF also supported a project examining the ability of eastern oysters to adapt to increasing CO_2 levels, determine whether any adaptive mechanism is transferred to progeny by epigenetic mechanisms, and explore the role of methylation in any epigenetic effects.

Theme 2. Monitoring of Ocean Chemistry and Biological Impacts

EPA continued sampling for carbonate parameters in its monthly nutrient and stable isotope surveys of Narragansett Bay to document biogeochemical responses to recent nutrient loading reductions. EPA collected samples for carbonate parameters at University of Rhode Island pH monitoring sites in order to leverage historic pH measurements. Using samples from these sites as well as controlled laboratory experiments, EPA began studies of the effects of organic matter and organic acids on carbonate system measurements in the coastal environment. EPA conducted coastal plankton incubation experiments examining the effects of nutrient enrichment on pH and dissolved inorganic carbon speciation. EPA also provided technical support to three National Estuary Program sites monitoring for pH and pCO_2, including Casco Bay (ME), Long Island Sound, Barnegat Bay (NJ), and Mass Bays (MA).

NOAA, Northeast Regional Association of Coastal Ocean Observing Systems, and University of New Hampshire continued operating an OA mooring in the Gulf of Maine. NOAA maintained underway OA observing equipment on a commercial ship conducting regular transits between Boston, Massachusetts and Iceland and on a NOAA ship that conducts fisheries independent trawl surveys in Northeast waters. In FY 2016 and FY 2017, sample and data analysis from the 2015 synoptic OA cruise of the east coast continued. NOAA funded carbon chemistry sampling during six Northeast Fisheries Science Center's Ecological Monitoring cruises.

NOAA funded 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 measuring total alkalinity, pH, and pCO_2 were used, including buoys and cruises, to improve the temporal and spatial coverage of OA monitoring from Long Island Sound to the Scotian Shelf. The project is developing threshold indices tied to acidification impacts on larval production at the Mook Sea Farm oyster hatchery in Maine.

Acadia National Park (ME) is working with the Schoodic Institute and others to investigate the impacts of OA on intertidal ecosystems. Acadia National Park deployed sensors and engaged professional scientists and citizen volunteers to study physical ocean changes and changes in intertidal species. The park is using scenario planning to identify best actions for addressing OA.

The Pioneer Array, an element of NSF's Ocean Observatories Initiative located between central New Jersey and Martha's Vineyard, Massachusetts, began releasing data in FY 2016, and provides considerable data to increase 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. In 2017, NSF funded a new LTER site, Northeast U.S. Shelf, focused on shelf waters of the Middle Atlantic Bight and Gulf of Maine. This LTER will utilize data from the OOI Pioneer Array. NSF supported a project to determine how alkalinity variations in the Gulf of Maine affect pCO_2 and aragonite saturation state.

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

EPA continued collaborating with Stony Brook University on a NOAA-funded project focusing on OA effects on resource shellfish populations, providing in-kind ecological modeling support. In addition, EPA scientists incorporated carbonate chemistry into water quality models used for research on the impacts of nutrient loading to coastal ecosystems.

NOAA estimated the vulnerability of Northeast fisheries species to changes in temperature and OA. NOAA explored the potential impacts of OA on the Northeast marine ecosystem and fisheries using an Atlantis ecosystem model. With the University of Maryland and Louisiana State University, NOAA used life-cycle modeling to study how OA may influence winter flounder populations.

NASA supported projects examining the carbon cycle and OA variability in coastal Gulf of Maine waters, with the aim of improving understanding of processes controlling carbonate system variability in coastal areas. These studies combine monitoring data, process studies, numerical modeling, and ocean color satellite data.

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

EPA continued investigating low-cost alternatives for handling and analysis of seawater OA samples.

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

EPA worked to finalize a bioeconomic model for valuing marine ecosystem services and assessing economic impacts from climate change and acidification on shellfish in the Gulf of Maine. The study provides insight into potential future impacts to the commercial shellfish sector.

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

The Northeast Coastal Acidification Network (NECAN) has become the leading organization for the synthesis and dissemination of regional ocean and coastal acidification data and information from Long Island Sound to the Scotian Shelf. 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. It also coordinates and develops regional priorities for science observing and research investments designed to further understanding of OA. NECAN is a joint Federal, academic, and industry partnership established under the Northeast Regional Association of Coastal and Ocean Observing Systems.

In FY 2016, NECAN released a redesigned website, adding region- and species-specific information. 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. NECAN developed practical guidance for future and existing OA programs in other regions to assist with improving their practices and infrastructure. NOAA and EPA provided funding and in-kind support for the NECAN workshops, web development, staff support, and other efforts. NECAN published a detailed OA scientific synthesis document and, with EPA, a practical guide to monitoring for ocean and coastal acidification. In addition, NECAN created a series of educational pamphlets and an animated educational video on OA.

NOAA created a training program for citizen-science monitoring in the northeast. Massachusetts Sea Grant and Woods Hole Oceanographic Institution are working closely with the Buzzards Bay Coalition to train staff and volunteers on the impacts of OA on shellfish and worked with the Sea Education Association's summer camp for high school students, SEAscape, to integrate physical transport of tracers and OA into educational programs. New Jersey Sea Grant added OA education to their annual summer camp program.

NSF provided support for a Research Experience for Undergraduates Site at the Mystic Aquarium in Mystic, CT focused on the consequences of global change, including OA, on marine ecosystems.

United States Mid-Atlantic

Theme 1. Research to understand implications of ocean acidification

EPA contributed coastal and OA data to the Mid-Atlantic Regional Council for the Ocean's Ocean Data Portal, which helps to inform resource managers and stakeholders to enhance decision making.

Virginia Sea Grant funded a project to determine the relative contributions of harmful algal blooms, OA, and microbiome alteration to production problems in eastern oyster and clam hatcheries and identify specific management strategies to alleviate them.

NSF funded a study of carbon cycling at the Delaware National Estuarine Research Reserve. NSF Integrative Ecological Physiology Program funded a project that examines the ability of an oyster and a species to build their shells at varying concentrations of CO_2 and in varying salinities. NSF also supported a collaborative project to examine carbon cycling in seagrass meadows in South Bay, Virginia; St. George Sound, Florida; and Lee Stocking Island, Bahamas.

Investigators at the Smithsonian Environmental Research Center (MD) examined patterns and effects of diel-cycling acidification and hypoxia typical of shallow waters of the Chesapeake Bay and coastal systems worldwide. They also developed a laboratory facility to conduct experiments that mimic environmentally

realistic exposures, and used it to study growth, tolerance, and behavior of two related fish species, the Atlantic silverside and inland silverside.

Theme 2. Monitoring of ocean chemistry and biological impacts

EPA analyzed pH, total alkalinity, and dissolved inorganic carbon in samples from nearly 200 stations in the Delaware River and Estuary and transects off the coast of Delaware and Chesapeake Bays for a baseline assessment of coastal and ocean acidification. This information increases understanding of the relationship between nutrients and acidification.

EPA co-led a monitoring workgroup with the Mid-Atlantic Regional Ocean Council to develop the framework for a regional monitoring infrastructure. This framework will guide future acidification research and make data available through the Ocean Data Portal. The Ocean Data Portal receives continued data management and contributions by EPA and other Federal agencies and collaborating Mid-Atlantic States.

NOAA funded a new OA mooring in the Chesapeake Bay and funded University of Maryland to collect OA measurements during three 5-day cruises spanning the entire Chesapeake Bay. Sample and data analysis from the 2015 synoptic OA cruise of the east coast continued with multiple publications released on the aragonite state and other carbon features. NOAA funded carbon chemistry sampling during six Northeast Fisheries Science Center's Ecological Monitoring cruises.

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

EPA integrated results from Theme 2 sampling activities in Delaware Bay into modeling studies of coastal acidification.

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 modeling tools will simultaneously simulate the dynamics of eutrophication, hypoxia, carbonate chemistry, and oyster reef growth and interaction with the water-column under present and future conditions.

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

In partnership with IOOS and the NOAA OA Program, the Mid-Atlantic Ocean Acidification Network (MACAN) launched in FY 2017. MACAN is a group of scientists, Federal and state agency representatives, resource managers, and affected industry partners dedicated to coordinating and guiding regional science on ocean and coastal acidification. MACAN works to develop a better understanding of the processes associated with estuarine, coastal, and ocean acidification, predict the consequences for marine resources, and devise local adaptation strategies that enable communities and industries to better prepare and adapt. MACAN also helps to fulfill the needs of other regional entities where objectives align, such as working with the Mid-Atlantic Regional Planning Body to help fulfill their needs as laid out in the Mid-Atlantic Regional Ocean Action Plan. MACAN serves as an information hub and exchange among research, industry, and resource managers focusing on waters and impacted species from south of Long Island to and including Virginia. Network members work collaboratively on identifying and pursuing opportunities to address coastal and ocean acidification in the Mid-Atlantic, building upon the skills and interests of individual members and providing a forum to share best practices in monitoring and sampling collection.

MACAN hosted four webinars to develop the state of the science and share scientific findings with interested academics and stakeholders. Following the webinar series, MACAN held an inaugural workshop

to bring stakeholders together to discuss ecological data gaps, stakeholders' needs and concerns, and monitoring plans. As a result of the workshop, MACAN decided to develop two workgroups to further develop ideas and strategies to create a regional monitoring plan and address research priorities. EPA provided in-kind support for the MACAN workshop as a facilitator, anticipates continued partnership through participation on the MACAN steering committee, and co-leads the monitoring workgroup.

NSF provided support for a Research Experience for Undergraduates Site at Old Dominion University for the Study of Metropolitan Coastal Environments and Communities, which includes OA and other environmental stressors in coastal waters.

United States Southeast and Gulf Coast

Theme 1. Research to understand implications of ocean acidification

NASA, NOAA, USGS, and university scientists continued a synthesis of coastal carbon data from the Gulf of Mexico.

EPA continued biological response experiments focusing on the combined effects of coastal acidification and hypoxia on marine organisms at its research laboratory in Gulf Breeze, FL.

NOAA Sea Grant funded Louisiana State University to study the impacts of OA on natural phytoplankton communities and the nutritional change this could have on oysters. NOAA's Coral Reef Conservation Program (CRCP) supported field-based research activities in Florida to understand the response of coral growth and calcification across natural gradients in CO_2, including work on restoration of *Acropora* coral, an Endangered Species Act-listed species.

NSF funded a project to study processes that affect pH in a river-dominated, eutrophic coastal region in the Gulf of Mexico.

Researchers at the Smithsonian Marine Station (Fort Pierce, FL) tested the combined effects of OA and algal overgrowth on the health of adult corals and the settlement and survival of juvenile corals. They also investigated whether changes in seawater pH and temperature influence coral larvae settlement.

USGS completed experiments in Dry Tortugas National Park to examine spatial heterogeneity of OA parameters on Pulaski Shoal and associated representative habitat types including seagrass beds, coral reefs, sand bottom, and reef rubble. USGS measured carbon chemistry of the West Florida Shelf and evaluated coastal carbon fluxes and submarine groundwater discharges, which act as stressors on coral reefs and other ecosystems. USGS developed numerical modeling systems for the flow patterns of and discharge rates into Biscayne Bay, FL, which may provide insight into causes of ecosystem degradation. Experiments were performed in Tampa Bay, FL to determine the potential for seagrass beds to buffer pH and modify carbonate saturation state and better understand the role of these processes in creating OA refuge conditions.

Theme 2. Monitoring of ocean chemistry and biological impacts

BOEM Environmental Studies Program, NOAA, and Texas A&M University continued a project to establish the Flower Garden Banks National Marine Sanctuary as a coral reef OA sentinel site. This project has matching resources provided by the Shell Exploration and Production Company. The project conducted chemical and biological monitoring to better understand how this system is changing and what attribution, if any, can be ascribed to OA.

The NPS and USGS partnered to monitor calcification rates in coral reefs in Dry Tortugas National Park, Biscayne National Park, and Buck Island Reef National Monument. The goal of this work is to establish baseline calcification rates for corals and calcareous algae and determine how they respond to increased OA. The NPS also partnered with NOAA to collect OA-relevant data within Dry Tortugas National Park, Everglades National Park, Biscayne National Park, and Padre Island National Seashore boundaries while the NOAA Gulf of Mexico Ecosystems and Carbon Cruise was off-shore taking complementary samples.

USGS completed design and construction of a second autonomous carbon system monitoring system for deployment in Tampa Bay, FL as part of a bay-wide OA monitoring program to examine the potential for seagrass in Tampa Bay to buffer the impacts of OA and as part of a larger effort for valuation of seagrass restoration and recovery in Tampa Bay. This work was funded by USGS Coastal and Marine Geology Program, Tampa Bay Estuary Program, EPA National Estuary Program, and Tampa Bay Environmental Restoration Fund.

Coastal Bends Bay National Estuary Program (TX) monitored pH and pCO_2, and Tampa Bay Estuary Program (FL) began procuring instrumentation for new coastal acidification observing system.

In FY 2017, NOAA led the third Gulf of Mexico Ecosystems and Carbon Cruise on the NOAA ship *Ronald H. Brown*. This was the most comprehensive OA cruise to date in this region, including sampling in the international waters of Mexico and Cuba for the first time. NOAA operated OA moorings at Gray's Reef, GA; Cheeca Rocks, FL; and coastal Mississippi. Analyses and synthesis of the data collected by the FY 2015 East Coast synoptic OA cruise, which included the Southeast region, continued with multiple papers published. The NOAA Fisheries ships *Gunter* and *Bigelow and UNOLS vessel Walton Smith* provide regular cruise tracks in the East Coast and Gulf Coast and sample surface CO_2 while conducting fisheries stock and ecosystem assessments. NOAA funded University of Southern Mississippi scientists to expand OA monitoring in the northern Gulf of Mexico with the addition of a buoy with a pH sensor and quarterly OA cruises.

NSF provided ongoing support for the Virginia Coastal Reserve LTER and Georgia Coastal Ecosystem LTER. Both sites collect time series data on carbon and nutrient cycling, biological communities, pH, and estuarine carbonate chemistry. NSF supported a study to examine the hydrological controls on CO_2 flux and the carbonate system in estuaries along the Texas coast.

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

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

NOAA funded Texas A&M University to model the relationships between estuarine acidification and other stressors in Texas estuaries. NOAA used a high-resolution regional ocean-biogeochemistry model to study the United States East and Gulf Coasts, examining future OA variability and providing an observational strategy suitable for elucidating the multi-annual trend of carbon and biogeochemical variables in the two regions. This model will fill the temporal gaps in OA understanding between the first three synoptic OA cruises in the regions. NOAA developed maps of aragonite saturation state, alkalinity, dissolved inorganic carbon, pCO_2, temperature, and salinity for the Mississippi River Basin and East Coast. This work is based on regionally-specific algorithms that use synoptic environmental datasets and are verified with observational data.

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

NOAA supported the preparation of the Southeast Fisheries Climate Vulnerability Assessment that will examine the vulnerability of 80 species in the Gulf of Mexico.

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

The Gulf of Mexico Coastal Acidification Network was established in FY 2016 as a collaboration between the Gulf of Mexico Coastal Ocean Observing System Regional Association, NOAA OA Program, Federal and state agency representatives, resource managers, industry partners and research scientists. The mission of the Network is to identify critical vulnerabilities of the Gulf of Mexico ecosystem that may be impacted by OA, foster collaborations to increase ocean observations, and develop strategies to mitigate impacts from OA. In FY 2017, Gulf of Mexico Coastal Acidification Network organized a state-of-the-science synthesis workshop and hosted eight webinars to inform stakeholders on changing ocean chemistry, biological sensitivity, and socio-economic impacts of OA in the Gulf of Mexico.

In 2016, the Southeast Ocean and Coastal Acidification Network held a state-of-the-science workshop. In 2017, NOAA funded SOCAN to host two workshops, which focused on coordinating engagement roundtables for stakeholders to learn about OA issues and discussing priority locations for OA monitoring, and two webinars.

NPS contributed to the Gulf of Mexico Ecosystems and Carbon Cruise blog and developed two articles about NPS's involvement in the cruise.

Caribbean

Theme 1. Research to understand implications of ocean acidification

USGS completed field experiments in Virgin Islands National Park to examine the environmental factors that create refuge conditions in mangrove habitats for reef building corals. Experiments focused on the interactions between water movement in these habitats and chemical, physical, and biological controls on OA parameters.

USGS supported studies on the effects of OA 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.

Theme 2. Monitoring of ocean chemistry and biological impacts

NOAA's CRCP 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 operated two sentinel sites for OA in the Atlantic Ocean basin: La Parguera, Puerto Rico and Cheeca Rocks, FL (see United States Southeast and Gulf Coast sections above). NOAA also 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 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 developed and released maps of aragonite saturation state, alkalinity, dissolved inorganic carbon, pCO_2, temperature, and salinity for the Caribbean Sea and Gulf of Mexico (see United States Southeast and Gulf Coast sections above).

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

NOAA continued to support the development of advanced technologies to quantify net community rates 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.

Theme 8. Other ocean acidification research and monitoring activities

NSF provided funds to the Central Caribbean Marine Institute to expand capacity at the Little Cayman Research Centre for both environmental research and education, which will improve the ability of the Centre to address OA.

United States West Coast

Theme 1. Research to understand implications of ocean acidification

EPA continued funding two OA studies through its STAR program. One focused on the effects of OA on estuarine phytoplankton dynamics. The other focused on the response of the shellfish toxic pathogen *Vibrio tubiashii* to changes in CO_2, dissolved oxygen, and temperature. EPA initiated mesocosm experiments focused on the impact of nutrient loading and residence time on the response of estuarine primary producers and the expression of eutrophication and included carbonate chemistry as response metric. These mesocosm experiments elucidate the role of seagrass in moderating acidified conditions.

NOAA maintained and improved upon its facility for conducting experiments on species response to OA, hypoxia, and climate change at the Northwest Fisheries Science Center (Mukilteo, WA). NOAA also invested in a second facility for conducting species response experiments at the Northwest Fisheries Science Center's Manchester, WA station. NOAA scientists studied Dungeness crab, pteropods, geoduck and krill under OA conditions, often with high temperature or low oxygen treatments. NOAA scientists also completed two meta-analysis to better understand the sensitivity of West Coast species to OA.

NOAA Sea Grant funded the following: University of California to determine the effect of OA and low oxygen on pregnant female rockfish, study the threat of winter runoff events and summer upwelling events on growth and survival of commercial and native oysters, and investigate the amount of carbon removed from seawater by seagrass beds; Oregon State University to study how vulnerable or resilient the life-stages of native shellfish are to OA and low oxygen, identify best management practices for shell planting and oyster culture to mitigate OA impacts, and develop a lesson plan for high school science students on the development and use of geochemical tools; and University of Washington to study pteropods as an indicator species of OA and the effects of OA on salmon and sablefish neurobehavioral function.

NOAA researchers worked with colleagues from the University of Washington, Puget Sound Restoration Fund, and Washington Department of Natural Resources to assess whether cultivated kelp can protect shellfish and other sensitive species from OA. This project is funded by the Paul Allen Foundation.

NPS worked with partners to use data collected in national parks to inform OA experiments. At Point Reyes National Seashore (CA), 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 (e.g., shellfish) 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 (CA) has teamed up with the University of California, Santa Barbara, to collect pH data generated by SeaFETs sensors.

NSF provided funds to Stanford University's Hopkins Marine Laboratory to upgrade an experimental system to facilitate research on multiple stressors, including OA. NSF supported projects focused on organism physiological changes in response to OA, organism responses that propagate through food webs and communities, OA-driven changes in nutrient cycles and ocean chemistry, and proxies that allow assessment of OA effects in past and contemporary oceans. These studies included work to determine whether populations of Olympia oysters are locally adapted to OA in North Pacific; the kinetics of calcium carbonate dissolution rates in North Pacific waters; boron to calcium ratios in sediment traps in the Santa Barbara Basin over the past 20 years; how predator-prey and trophic relationships in rocky intertidal communities are influenced by varying levels of pH; how recovery of the keystone species ochre sea star, *Pisaster ocraceus,* is affected by environmental stressors, including variations in pH; how changes in pH and other environmental drivers affect the swimming behaviors and vertical distributions of coastal zooplankton populations; and how abalone populations respond to local variations in ocean environmental conditions, including OA, temperature, and oxygen.

Theme 2. Monitoring of ocean chemistry and biological impacts

The IWG-OA and Pacific Coast Collaborative jointly created the West Coast OA Task Force. The Task Force inventoried all chemical and biological monitoring assets from Alaska to California and developed maps to display known assets. These products will be used for gap analysis efforts to inform monitoring investments.

EPA funded and helped conduct a study focused on carbonate chemistry dynamics in nearshore shellfish habitat in Puget Sound. This project identified local factors influencing carbonate chemistry dynamics and is a collaboration with USGS, Oregon State University, the State of Washington, and Tulalip Tribes. EPA also collaborated with USGS, Oregon State University, and Tillamook Estuaries Partnership to study the local drivers influencing carbonate chemistry dynamics in Tillamook Estuary, Oregon, which is part of the National Estuary Program. This estuary is influenced by ocean conditions as well as watershed inputs such as wastewater treatment facility effluent and agricultural activities. In collaboration with the US Navy Research Laboratory, EPA began developing a model to identify local drivers influencing acidification in Tillamoook Bay.

The NPS partnered with NOAA in the summer of FY 2016 to collect OA-relevant data within Olympic National Park (WA) and Cabrillo National Monument (CA) during the NOAA West Coast OA cruise.

EPA provided funding to the San Francisco Estuary Partnership (CA) for the procurement of a pH and pCO_2 monitoring system. Santa Monica Bay National Estuary Program (CA) deployed pH and pCO_2 instrumentation previously funded by EPA.

NOAA funded a synoptic OA cruise of the West Coast in summer 2016. This cruise sampled from the northern Baja California Peninsula to the top of Vancouver Island upon the NOAA ship *Ronald H. Brown*. In addition to extensive seawater carbon chemistry sampling, cruise participants collected samples to study oxygen concentration, salinity, macro-nutrients, pteropod distribution, crab larvae, copepods, krill, and phytoplankton, including harmful algal bloom species.

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 conducted regular OA-related monitoring at the Olympic Coast National Marine Sanctuary (WA). Additionally, 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. With an award from California's Ocean Protection Council, NOAA and partners worked with the Hog Island Oyster Company to install a state-of-the-art monitoring instrument to track Humboldt Bay's carbonate chemistry at the company's new oyster hatchery.

NPS monitored seawater carbonate chemistry conditions at Cabrillo National Monument (CA), Olympic National Park (WA), and San Juan Island National Historical Park (WA). OA monitoring at each site is coupled with the long-term intertidal monitoring observations, which will provide managers and researchers with the tools they need to understand the impacts of OA on intertidal systems.

The Coastal Endurance Array, an element of NSF's OOI located off the coast of Oregon and Washington, 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 and ship time at the California Current Ecosystem LTER site. NSF supported a project to assess how water column chemistry is altered within kelp forests.

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

NOAA scientists collaborated with the Department of Energy's Pacific Northwest National Laboratory to investigate how the diel movements of zooplankton in the Puget Sound, WA, influence their CO_2 exposure under current and projected future conditions.

An expanded model examining how regional freshwater/land-derived sources of nutrients impact acidification in the Salish Sea was completed through a partnership between the EPA, Washington Department of Ecology, and Pacific Northwest National Laboratory in June of 2017. This model provides important information for land and coastal managers regarding geographic variability and seasonality in water chemistry influenced by regional sources of nutrients. The report identifies potential next-steps and management actions.

Through its Saltonstall-Kennedy grant program, NOAA funded the San Jose State University Research Foundation to forecast the effects of OA and hypoxia on reproduction of West Coast groundfish. NOAA funded a number of modeling projects in the California Current region including an ocean hypoxia and acidification model that can be used to understand the relative contributions of natural climate variability versus anthropogenically induced climate change, a model to predict current and future carbon chemistry measurements (Oregon State University), and a model to generate seasonal forecasts of ocean carbonate chemistry and other conditions in the Pacific Northwest (University of Washington). The latter model now generates six-month forecasts of dissolved inorganic carbon, total alkalinity, pH, oxygen, and calcite/aragonite saturation twice a year, and is being extended to forecast impacts on Dungeness crab and

shellfish. NOAA, University of Washington, and Australian scientists modeled how the effect of OA may impact West Coast food webs, fisheries harvests, and regional economies. NOAA's Cordell Bank and Greater Farallones National Marine Sanctuaries (CA) worked in partnership with Point Blue Conservation Science and University California Davis to characterize carbonate chemistry conditions in the two sanctuaries, develop a region-specific model, and determine biological impacts.

NSF made two awards to the University of California to examine the dynamics of upwelling variability off the coast of California and develop a predictive model to assess OA in this dynamic coastal region.

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

IOOS and NOAA supported OA sensor development and application, targeting shellfish industries across the United States West Coast, Alaska, and Hawaii. NOAA Sea Grant funded researchers at Oregon State University to develop an inexpensive tool for oyster growers to assess the condition of oyster seed and juveniles in real time. NOAA continued work to evaluate the best carbon system technologies to deploy in subsurface waters, demonstrate the utility of these enhanced observations at the mooring off Washington, and make recommendations on how advanced technologies can be incorporated into OA monitoring programs.

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

NOAA scientists participated as panelists on the West Coast Ocean Acidification and Hypoxia Panel, which was partially funded by the FWS Coastal Impact Assistance Program. The Panel developed products that synthesize the state of knowledge related to OA, identify science-based options to address OA at regional and local levels, and serve as a scientific call to action.

BIA funded the Lummi Nation’s Natural Resources Department to prepare a comprehensive plan for managing harvest of intertidal shellfish resources under existing and potential climate change impacts.

EPA worked to finalize a bioeconomic model for valuing marine ecosystem services and assessing economic impacts of climate change and acidification on shellfish in the Puget Sound.

NOAA continued a project to assess the socio-cultural vulnerability and resilience of tribal and non-tribal coastal communities to OA in Washington. NOAA funded the University of California Davis and Pacific Shellfish Institute to quantify the functional relationships between shellfish culture and seagrass in West Coast estuaries. NOAA and University of California Davis scientists worked with California legislators to summarize the research and develop recommendations on how seagrass may be used to address OA. In addition, NOAA funding assisted in the development of an OA-tolerant urchin strain.

The Olympic Coast National Marine Sanctuary convened a workshop with regional partners to define the Olympic coast as an “OA sentinel site.” Priority needs identified during the workshop and a survey conducted prior to the workshop, call for integration of chemical and biological data from ongoing monitoring efforts and to identify where coupled biological and social vulnerability to OA is highest.

The NOAA Saltonstall-Kennedy program funded University of Washington to research mitigating the effects of global change, including OA, on aquaculture in the northeastern Pacific Ocean and University of California Davis to study adapting red abalone aquaculture to changing ocean conditions. NOAA scientists participated in a project funded by the Paul Allan Foundation to assess the ability of kelp aquaculture to

mitigate OA at local scales.

NOAA supported the West Coast Climate Vulnerability Assessment that examined the vulnerability of 65 West Coast fish stocks and 33 salmon distinct population segments in the region to climate change, including OA. This Assessment was linked to NOAA Fisheries Social Indicators to examine the climate vulnerability of West Coast coastal communities.

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

Washington Sea Grant coordinated a blog for the 2016 West Coast OA cruise, which was mirrored on multiple agency and partner sites. NOAA led mission-related outreach activities during the cruise's port calls at the San Francisco Exploratorium and in Seattle. NPS used the cruise as an opportunity to educate the public about OA and explain how the NPS addresses it. Scientists from Cabrillo National Monument (CA) contributed to the cruise blog and published an article on nps.gov about NPS participation in the cruise. This effort inspired dedication of a fall 2016 NPS newsletter to the issue of OA.

Multiple agencies and Oregon State University convened a "fishermen-scientist roundtable" to discuss current science and fishermen observations related to OA and climate change for species including pink shrimp, Dungeness crab, and pelagic fish. The discussion focused on fostering improved interactions between scientists and fishermen, increased collaborative research between scientists and fishermen that provides mutual benefits to science and fishing communities, and identifying key species for which limited research exists regarding impacts of OA. The California Current Acidification Network, launched in 2010, continued to create a community of OA stakeholders along the United States West Coast. The Network hosted two webinars.

NOAA partnered with Flathead Valley Community College to pilot the pHyter, a low-cost, hand-held device, with an associated app, designed to measure pH that can be used in education and outreach programs. NOAA fostered communication between technical experts and stakeholders as an important contributor to the Washington Marine Resources Advisory Council's 'refresh' of the Washington State Blue Ribbon Panel's 2012 OA recommendations. NOAA's Pacific Marine Environmental Laboratory worked with data visualization designers and programmers at the University of Washington and Rhode Island School of Design to develop interactive tools to visualize observational data generated by the NOAA Ocean Acidification Observing Network and create 3D animations of seasonal forecasts of OA in the Pacific Northwest.

Washington Sea Grant's OA educational work, which included presentations and trainings, reached hundreds of people throughout the region. Oregon Sea Grant partnered with representatives from academic institutions and non-governmental organizations to develop a series of videos on the actions and solutions underway in Oregon to address OA. California Sea Grant funded a workshop for 50 scientists, managers, and representatives of local monitoring entities to develop an OA monitoring framework for San Francisco Bay.

The NPS Natural Resources Stewardship and Science Directorate partnered with Cabrillo National Monument (CA) on the development of a graphically-rich "explainer" video that explores the science and ramifications of OA. It will be used in formal and informal programs with students, visitors, and online audiences.

Theme 7. Data management and integration

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

Alaska

Theme 1. Research to understand implications of ocean acidification

EPA funded a graduate fellowship at the University of Texas Austin through the STAR project to focus on the effects of OA on algae and invertebrates in Alaskan and Chilean kelp ecosystems.

NOAA maintained experimental facilities at the Alaska Fisheries Science Center's Kodiak, AK, and Newport, OR, laboratories to study the response of Alaskan marine species to OA. Research at these facilities focused on northern rock sole, walleye pollock, Pacific cod, speckled sand dab, red king crab, blue king crab, golden king crab, snow crab, southern Tanner crab, and *Primnoa* coral. Alaska Sea Grant funded a project on the impact of OA on dogfish's ability to track food and other resources.

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

BIA gave a grant to the Chugach Regional Resources Commission, an inter-tribal fish and wildlife commission, to build an OA experimental system at the Allutiq Pride Shellfish Hatchery in Seward, AK to study the effects of OA on shellfish larvae. Initial research at this laboratory has focused on shellfish customarily harvested by indigenous people, especially the littleneck clam.

Theme 2. Monitoring of ocean chemistry and biological impacts

Analysis continued from the 2015 Gulf of Alaska synoptic cruise, which was funded by NOAA and NSF to characterize the carbon chemistry, primary production, and zooplankton communities of the Gulf of Alaska. This cruise worked to identify differences in sea-air exchange between various types of surface water, including ice melt.

The Distributed Biological Observatory is a multidisciplinary, international Arctic Ocean sampling program supported by multiple Federal agencies which includes eight regularly sampled hot spots off the coasts of Alaska. The FY 2017 Distributed Biological Observatory cruise collected over 500 samples for dissolved inorganic carbon and total alkalinity analysis in the Bering and Chukchi Seas.

Kenai Fjords National Park partnered with USGS to study how the increase in the amount of freshwater entering the marine ecosystem impacts the nearshore ecosystem.

BOEM funded a study that deployed oceanographic SeapHOx sensors along a Cook Inlet freshwater gradient. The study objectives are to establish baseline measurements and to quantify the sources of pH variability. The results from this study will support analysis of cumulative effects in future NEPA documents for lease sales, as well as exploration and development plans.

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. OA observations on the Seward line ended in fall 2017.

NOAA continued to operate two coastal OA moorings in the Gulf of Alaska located in critical fishing areas. Analysis of data collected during the FY 2015 deployment of a mooring in the Chukchi Sea continued. The region has also been targeted by research cruises, volunteer observing ships, and autonomous underwater vehicles for other monitoring and process-based work throughout much of the five Large Marine Ecosystems that comprise Alaska's marine waters. As noted above under the 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 deployed wave gliders in the Bering Sea, and two newly developed ASV-CO_2 Saildrones, autonomous wind-and-solar-powered vehicles, sailed from Dutch Harbor through Bering Strait to the Chukchi Seas. Together, these three deployments assessed the relationship between CO_2 fluxes and respiration that place critical controls on the duration and persistence of OA events in Arctic systems. NOAA and Alaska Ocean Observing System staff worked to install a system to monitor OA in surface waters onto the M/V *Columbia* which takes weekly runs from Washington State to Alaska.

Glacier Bay National Park partnered with the University of Alaska Fairbanks to investigate the potential correlation between OA and zooplankton health within the glacial fjord system in Glacier Bay.

NSF funded a new ocean LTER site in the Northern Gulf of Alaska which will continue the long-term data observations at this location, including characterization of the ocean carbon cycle and biota.

BIA provided funding to the Chugach Regional Resources Commission to monitor OA in south-central Alaska. Commission member tribes, Seldovia Village Tribe, Kasitsna Bay Lab (NOAA), and Kachemak Shellfish Mariculture Association collected weekly seawater chemistry samples from their docks; the Prince William Sound Science Center collected seawater chemistry samples on its annual cruise; and the Kachemak Bay National Estuarine Research Reserve (NOAA) collected seawater chemistry samples during its regular sampling events. This project has expanded OA near-shore monitoring, enabled Alaska native coastal communities in south-central Alaska to obtain information on OA that is specific and relevant to their local environment, and helped climate scientists investigate the linkages of off-shore sampling to the near-shore.

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

NOAA supported incorporation of the potential impacts of OA into recruitment and population dynamics models of three Alaska crab stocks and used these population forecasts in linked bioeconomic models of fisheries yields and profits.

The NPS Alaska Region, along with Glacier Bay National Park, is partnering with the University of Alaska Fairbanks to develop a regional OA model. They are taking a systems-based approach to a conceptual model of OA focusing on trophic linkages between nearshore coastal communities and nearshore coastal dynamics, with consideration for the physio-chemical characteristics and 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 supported the Alaska Fisheries Climate Vulnerability Assessment that examined the vulnerability of 36 fish stocks in the Eastern Bering Sea to climate change, including OA. The Alaska Fisheries Climate Vulnerability Assessment was linked to NOAA Fisheries Social Indicators to examine the climate vulnerability of coastal communities. The NOAA-supported bioeconomic model for the Bristol Bay red

king crab fishery discussed above was linked to a regional economic model of Alaska's economy to assess the long-term cumulative economic impacts of OA on Alaskan households.

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

NOAA helped launch the Alaska OA Network in FY 2016 as a founding member, active collaborator, and funder. The Network interacts with fishing and aquaculture industries, policy makers, and coastal communities; identifies knowledge gaps; shares best practices for monitoring and strategies for funding; and is a resource hub for information about OA. The Network has established a comprehensive website, monthly listserv, initial set of outreach materials, and growing list of participants from multiple sectors. The Network held a "State of the Science" workshop which brought together experts and stakeholders from across Alaska. At the workshop, 250 state and national researchers discussed the growing need for a monitoring build-out plan for Alaska and an initial set of maps were developed showing an inventory of research efforts. An educator session was part of the workshop and was attended by 97 students from three Anchorage schools. The Network was able to hold question and answer sessions with stakeholders, fund speakers to give keynote talks on OA, produce updated outreach material, and purchase kits for high school teachers to perform hands-on OA experiments with their students.

NOAA's Alaska OA Network engaged educators in FY 2017 to discuss ideas and resources for incorporating OA into Alaska classrooms, identifying needs for curriculum, resources, and information. The resources identified from this discussion were incorporated into a webpage for the OA education on the Alaska OA Network website.

Alaska Fisheries Science Center scientists gave numerous presentations to public audiences and routinely participated in outreach events to educate the general public. They also produced displays to describe the basics of OA and the results from ongoing NOAA research on commercial crab species. A display is placed in the public visitor's section of the Kodiak Fisheries Research Center, which receives 12,000 annual visitors in the third largest fishing port in the United States.

NOAA supported the OA information needs of Alaska tribes, educators, and other stakeholders with presentations by Washington Sea Grant at a number of regional conferences.

United States Pacific Islands

Theme 1. Research to understand implications of ocean acidification

NOAA supported a synthesis of OA observations and projection models of oceanic carbonate system to coral reef-scale OA impacts. As a part of NOAA's CRCP, NOAA supported research on the impact of multiple stressors (temperature and OA) on recruitment, biomass, biodiversity, production and removal of calcium carbonate, and community structure of coral reefs over a multiannual time frame to increase understanding of how biodiversity, ecosystem function, and their relationship will be impacted under future climate scenarios. NOAA's Pacific Islands Fisheries Science Center initiated laboratory-based response experiments to examine impacts of OA on the biodiversity of cryptic reef organisms. Sea Grant funded gene expression work to understand the response of oysters to temperature change and OA.

NSF funded a study of the dynamics of water flow over different coral reef systems in the South Pacific, South China Sea, and Red Sea. The research will lead to a better understanding of wave-generated hydrodynamics on coral reefs that will allow for better estimates of CO_2 exchange and calcification or

dissolution. NSF also supported a study of diversity of coral reefs at Milne Bay Provence, Papua, New Guinea across a pH gradient created by natural CO_2 seeps.

USGS completed field experiments and monitoring exercises to determine the potential impact of groundwater and nutrients on acidification and bioerosion of coral reefs along the coastline of West Maui, HI. This research was performed in collaboration with the State of Hawaii Division of Aquatic Resources and will inform State coastal resource managers on the impact of local water treatment and disposal practices on coastal coral reefs.

Theme 2. Monitoring of ocean chemistry and biological impacts

NOAA operated four coral-reef OA moorings off Oahu, HI, 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 CRCP 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. In FY 2016 and FY 2017, NOAA monitored the progression and impacts of OA at a number of coral reef sites around the Pacific Ocean, including the Northwestern Hawaiian Islands, Guam, Wake Atoll, and Commonwealth of the Northern Mariana Islands.

The NPS Inventory and Monitoring program conducted monitoring to understand long-term changes in marine pH.

NSF continued to support OA research and monitoring at the Moorea Coral Reef LTER site in French Polynesia.

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

NOAA's Pacific Islands Fisheries Science Center built statistical models of the environmental drivers of net carbonate accretion rates, including aragonite saturation state and pH, across the vast, widely-separated U.S. Pacific Islands. These models allow better prediction of reef accretion under changing OA conditions. In addition, NOAA incorporated the consideration of OA into ecosystem models for insular and coral reef ecosystems to inform management strategy evaluations in the Pacific Islands.

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

An IOOS and NOAA-funded project tested a remote controlled, prototype dissolved inorganic carbon analyzer at a new buoy off Hawaii. NOAA continued work 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 could be incorporated into OA monitoring programs. Field work for this project began in Kaneohe Bay, HI in FY 2016.

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

NOAA's Pacific Islands Fisheries Science Center worked on multiple Climate Vulnerability Assessments that included consideration of OA, including examining the vulnerability of 85 fishery species and the socio-ecological vulnerability of coral reef ecosystems.

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

A NOAA and National Marine Sanctuary Foundation (NMSF) workshop was held to assess regional vulnerabilities of natural resources and ecosystem services to climate change, including OA, and to develop adaptation actions for the National Marine Sanctuary and Territory of American Samoa. NOAA and the NMSF also funded a program in which students from American Samoa learned about climate change and OA with hands-on activities.

OA was included in Kalaupapa National Historical Park presentations to the general public, local college extension courses, and community. OA is a component of the outreach that the Pacific Islands Inventory and Monitoring Network does on a regular basis through publications and presentations. The Pacific West Regional Office worked with a University of California Berkeley intern to add a coral reef toolkit page to the Office's Climate Change Toolkit; it includes information on OA as a stressor on corals.

The NPS Pacific West Regional Office Ocean & Coastal program entered into an agreement with the University of Hawaii Hilo to work with the four coral reef parks to recruit and engage college interns to create multimedia education and outreach materials on coral reefs focused on the local community, blending local traditional knowledge with park management data and information. OA will be one of the main topics discussed in all of the parks' materials.

Theme 8. Other research and monitoring activities

NSF provided funds to the University of California Berkley to upgrade cyberinfrastructure at the Gump Station, Moorea, French Polynesia that will enhance their ability to handle data related to studies on the effects of OA on coral reef systems as well as other research efforts.

Arctic

Theme 1. Research to understand implications of ocean acidification

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

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.

Theme 2. Monitoring of ocean chemistry and biological impacts

NOAA, BOEM, and Shell Exploration and Production Company funded a Marine Biodiversity Observation Network project in the Chukchi Sea, which included OA observations.

The BOEM-funded Marine Arctic Ecosystems Study includes two Beaufort Sea moorings that have OA sensors. BOEM has an additional mooring near the Boulder Patch Area of Special Biological Concern in the Beaufort Sea. Data from this sensor will detect seawater pH variation in relation to freshwater run-off. Data from these Arctic moorings will also facilitate a better understanding of oceanic uptake of CO_2 in the Arctic and potential effects related to offshore oil and gas activities.

NOAA operated an OA mooring in the North Atlantic off Iceland. In FY 2017, NOAA led a 21-day marine ecosystem research cruise aboard the U.S. Coast Guard *Healy* in the Northern Bering and Chukchi Seas. The cruise visited the long-term sampling locations of the NOAA Distributed Biological Observatory, which is an internationally endorsed project via the Pacific Arctic Group (US, Canada, China, Japan, Korea and Russia). NOAA operated two Saildrone missions: One mission was used as a test of the surface ocean pCO_2 system and the second completed a round-trip voyage of 7,509 nautical miles through the Bering Sea, Bering Strait, Chukchi Sea, and Beaufort Sea.

In FY 2017, NSF funded a new LTER located in the Beaufort Sea, Beaufort Sea Lagoons: An Arctic Coastal Ecosystem in Transition. This LTER will collect long-term data on primary productivity, nutrient cycling, the carbonate system, and other data relevant to OA research. NSF also funded a project to examine how the sea ice biota are affected by increasing CO_2 concentrations in conjunction with diminishing ice cover.

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

NOAA began supporting an Arctic OA modeling project aimed at developing a high-resolution, aragonite-saturation-state model for the Bering Sea which can produce both hind cast simulations and projections.

NSF supported a collaborative modeling exercise using existing data to evaluate processes controlling OA and carbon cycling in the Chukchi Sea.

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

BOEM, working with the University of Alaska Fairbanks, provided ongoing support to the development of a custom made-MiniPro CO_2 sensor with a Slocum glider. Several sea trials were completed in FY 2016 and FY 2017 off Seward, AK in the Gulf of Alaska and in the Chukchi Sea. Results from this study will facilitate a better understanding of oceanic uptake of CO_2 in the Arctic and potential effects related to offshore oil and gas activities.

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

The United States elevated OA as a priority initiative during its chairmanship of the Arctic Council from April 2015 to May 2017 and sought ways to enhance monitoring of OA throughout the entire Arctic Ocean. DOS, NOAA, the Natural Resources Defense Council, and the Finnish Meteorological Institute co-sponsored an Arctic workshop in Helsinki, Finland in October 2016 to address the economic and societal vulnerabilities to OA and promote the development of a cohesive OA-adaptation strategy that could be applied to the entire Arctic region (also discussed in Global section).

The Smithsonian Environmental Research Center provided funding to the non-profit Ocean Research Project to conduct a series of pCO_2 and total alkalinity measurements in a 1300-mile long survey of Inglefield and adjacent fjords in northwestern Greenland.

Antarctic

Theme 2. Monitoring of ocean chemistry and biological impacts

NSF continued supporting observations in coastal waters of the Antarctic Peninsula at the Palmer Antarctic LTER site. NSF also supported a one-year survey of the carbonate system in the Southern Ocean West Antarctic Peninsula that utilized an autonomous vehicle to obtain high-temporal regional coverage.

Appendix

Summary of Federally-funded Ocean Acidification Research and Monitoring Activities

Table 1. Summary of Federally-funded ocean acidification research and monitoring activities in dollars (thousands). The first value in each entry is for contributing activities that were designed for other purposes but clearly provide information useful for understanding OA, the second for activities having a primary focus on OA, and the third for the sum of primary and contributing activities.[1]

Theme	FY	BOEM	DOS	EPA	NASA	NOAA	NPS	NSF[2]	SI[3]	USGS	ALL
1. Research	'16			287/23/310	250/-/250	208/2730/2938	-/14/14	-/3940/3940	-/137/137	-/590/590	745/7434/8179
	'17			226/-/226	250/-/250	268/2422/2690		-/4043/4043	-/16/16	-/565/565	744/7046/7790
2. Monitoring	'16	-/35/35		115/315/431		3265/4813/8077	-/402/402	10262/2646/12908	-/54/54	-/145/145	13642/8411/22052
	'17	-/211/211				3788/4929/8717	-/234/234	13952/1776/15728	-/32/32	-/145/145	17740/7327/25067
3. Modeling	'16				250/-/250	52/1213/1265	-/10/10	-/1729/1729			302/2952/3254
	'17				250/-/250	20/1323/1343		-/499/499			270/1822/2092
4. Technology	'16	36/36/72			100/-/100	680/998/1678		-/664/664		-/80/80	816/1778/2594
	'17				100/-/100	1004/706/1710		561/733/1294		-/180/180	1665/1619/3284
5. Socioeconomics	'16		-/14/14	-/39/39		108/305/412	-/45/45				108/403/1546
	'17		-/0.3/0.3	-/47/47		83/1460/1543					83/1507/1590
6. Education	'16		-/600/600	48/-/48		76/87/163	-/19/19	1417/-/1417	5/-/5	-/15/15	1546/721/2267
	'17		-/434/434	4/-/4		65/100/165	-/2/2	1472/-/1472		-/15/15	1541/551/2092
7. Data management	'16					530/637/1168		750/-/750	-/9/9		1280/646/1927
	'17					433/871/1304		750/-/750			1183/871/2054
8. Other	'16				100/-/100	573/969/1542		418/-/418			1091/969/2060
	'17				100/-/100	803/1028/1831		524/-/524			1427/1028/2455
TOTAL	'16	36/71/107	-/614/614	450/378/828	700/-/700	5492/11752/17243	-/490/490	12847/8979/21826	5/200/205	-/830/830	19530/23314/42843
	'17	-/211/211	-/434/434	230/47/277	700/-/700	6464/12839/19303	-/236/236	17259/7051/24310	-/48/48	-/905/905	24653/21771/45724

[1] 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 it.
[2] All NSF research proposals contribute to education, outreach, and engagement through "broader impacts". CAREER research proposals also have well integrated educational components. These contributions could not be separated out from the research contributions, so the NSF contributions are under-reported. Ship support for NSF research activities is provided by NSF-funded University-National Oceanographic Laboratory System and is a major expense for activities in themes 1, 2, and 3. These expenses are not included in this summary table.
[3] Although the Smithsonian Institution did receive Federal appropriations in FY 2016 and FY 2017, none was designated directly for support of OA research, monitoring, technology development, or other activities. 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 2016 and FY 2017. Likewise, funding acquired through external grants and contracts, as well as any internally sourced funding, is accounted for in this report.