SIXTH REPORT ON FEDERALLY FUNDED OCEAN ACIDIFICATION RESEARCH AND MONITORING ACTIVITIES

A Report by the

INTERAGENCY WORKING GROUP ON OCEAN ACIDIFICATION

SUBCOMMITTEE ON OCEAN SCIENCE AND TECHNOLOGY
COMMITTEE ON ENVIRONMENT

of the
NATIONAL SCIENCE & TECHNOLOGY COUNCIL

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About the Interagency Working Group on Ocean Acidification

The Interagency Working Group on Ocean Acidification (IWG-OA) advises and assists the Subcommittee on Ocean Science and Technology on matters related to ocean acidification, including coordination of Federal activities on ocean acidification and other interagency activities as outlined in the Federal Ocean Acidification Research and Monitoring Act of 2009[1].

About this Document

This document was developed by the IWG-OA and published by OSTP. It meets the requirement of the Federal Ocean Acidification Research and Monitoring Act of 2009[1] to produce a biennial report to Congress on Federal ocean acidification activities. The previous biennial report covered FY16 and FY17, and can be found on the IWG-OA's website here.

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[1] 33 U.S.C. § 3703.

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List of Acronyms

BIA	Bureau of Indian Affairs
BOEM	Bureau of Ocean Energy Management
CO_2	carbon dioxide
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
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
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
NSF	National Science Foundation
NSTC	National Science and Technology Council
OA	ocean acidification
OSTP	Office of Science and Technology Policy
pCO_2	partial pressure of carbon dioxide
ppm	parts per million
USGS	United States Geological Survey

Introduction

Ocean acidification (OA), the reduction in ocean pH caused primarily by uptake of anthropogenically released carbon dioxide (CO_2) from the atmosphere, is a threat to marine ecosystems and the services those systems provide to society. This document summarizes Federal activities on OA in Fiscal Years (FY) 2018 and 2019. It is organized into sections corresponding to the nine geographic regions in which Federal agencies studied OA in FY 2018 and FY 2019, 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*, and then by Federal agencies. 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 2018, Federal agencies provided approximately $28.9 million (M) toward activities with a primary focus on OA and an additional $40.4 M for contributing activities. In FY 2019, Federal funding was approximately $26.7 M for primary activities and $75.3 M 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 Responses to 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 several awards focused on the effects of ocean acidification, and the interplay of OA and temperature stressors, on corals, including organismal responses on short time scales, seasonal to inter-annual responses of reef calcification, and the mechanisms of coral skeletal nucleation. NSF-funded studies of OA impacts on phytoplankton included: experimental studies of algal-bacterial interactions; molecular and physiological responses to changing ocean chemistry in upwelling systems; and iron uptake rates and iron acquisition strategies in the laboratory and in natural phytoplankton communities. Another study focused on the effects of OA on several species of shrimp.

NSF funded two new projects with implications for documenting the history of ocean pH, one focused on calibration of paleo proxies in deep-sea corals and the other on refining understanding sea-floor dissolution of calcium carbonate and its effect on proxy records.

Theme 2. Monitoring of Ocean Chemistry and Biological Impacts

NOAA and NSF supported global hydrographic surveys as part of the international Global Ocean Ship-based Hydrographic Investigation Program. This program provides high-quality, high spatial and vertical resolution measurements of a suite of physical, chemical, and biological parameters, including dissolved inorganic carbon, total alkalinity, and pH throughout the full water column in open-ocean waters. Surface CO_2 measurements from this program, moorings, and ships of opportunity are collated in the Surface Ocean CO_2 Atlas. As of June 2019, the Atlas contained 25.7 million observations of surface ocean partial pressure CO_2 collected between 1957 and 2019. 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 satellite mission. This mission addressed OA by improving the understanding of 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 2019, NASA's Coral Reef Airborne Laboratory project, one of the Earth Venture Suborbital-2 investigations, concluded its investigations. This project was 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 provided high-density observations of reef condition for a large, representative portion of the world's reefs, including Australia's Great Barrier Reef, Hawaii, the Mariana Islands, Palau, and the Florida reef tract

NOAA conducted OA cruises within U.S. coastal waters extending out to the economic exclusion zone. It also maintains 21 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, which have the sensor suite for maintaining an OA time-series. OA international buoy locations are: North Pacific, Bay of Bengal, Arctic Ocean north of Iceland, off the west coast of Chile, and off the island of Chuuk in the South Pacific. NOAA maintains an additional 8 open-ocean moorings that collect CO_2 data from surface seawater and marine boundary air to evaluate the variability in CO_2 exchange between the atmosphere and ocean. 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 research vessels in coastal and international waters to constrain the flux of CO_2 across the air-water interface.

A NSF-funded project used carbon isotope data from the Global Ocean Ship-based Hydrographic Investigation Program to determine decadal-scale trends in anthropogenic carbon in the world's oceans. 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 Time-series Study 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 vessels provided significant ship support for sampling at these stations and for numerous other projects. The NSF Ocean Observatories Initiative continued global ocean buoy observations at two sites: Station Papa in the North Pacific Ocean and a site in the Irminger Sea, North Atlantic Ocean. NSF continued support for a project to combine research on the feedback between the cycling of major ocean cations in seawater

and the global carbon cycle. An NSF-funded project is focused on improving marine inorganic carbon system measurements, and another on accurately characterizing the solubility of biogenic calcium carbonate.

Theme 3. Improving Models of the Effects of Ocean Acidification on Ecosystems and Society
NOAA's earth system modelling efforts 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, including analysis of time of emergence of OA and other biogeochemical signals, (2) prototyping models at high resolution with highlights including the signature of natural OA associated with El Niño-Southern Oscillation variability in the California Current System, and (3) implementation of the next generation coupled model for participation in the 6th Coupled Model Intercomparison Project, which includes historical and future projections with OA. This work provided OA model data to the public at an unprecedented 1/4 degree global resolution and finalization of the fully coupled chemistry-carbon-climate Earth System Model ESM4.1.

NOAA also published findings on the global distribution of pH which quantified the controlling mechanisms of pH from temperature, pressure, biological activities, and calcium carbonate dissolution.

NSF initiated support of a five-year award focused on improving decadal-scale predictions of ocean biogeochemistry, with one of the main targets of investigation being OA.

Theme 4. Technology Development and Standardization of Methods
NOAA continued work with Saildrone, Inc. to field test the capacity of this wind- and solar-powered, autonomous surface vehicle for carbon dioxide measurements. In 2019, a Saildrone outfitted with sensors to monitor air and sea carbon dioxide levels, circumnavigated Antarctica, a journey of 13,670 miles. NOAA also worked on developing a coastal density glider that can profile shallow water columns for 3 months and developing an open-source, 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, a commercial total alkalinity sensor, and direct measurement of carbonate ion concentrations *in situ*. NOAA also funded work on structural engineering for offshore macroalgae farming, which could potentially reduce the rate of OA in local areas.

NOAA worked to develop, calibrate, and demonstrate the efficacy of Argo profiling floats equipped with temperature, salinity and biogeochemical sensors for pH, oxygen, nitrate, and optical observations to observe biogeochemical properties in the upper 2000 meters with sufficient accuracy for climate studies. This work will advance the ability to monitor and forecast changes in global ocean warming, acidification, deoxygenation, and marine ecosystem health. These are now known as the Biogeochemical Argo floats.

NSF continued to support the production of CO_2 reference standards for dissolved inorganic carbon and total alkalinity. It also supported two technology projects focused on OA research, one to integrate

carbonate system measurements on the SeaCycler moored profiling system and the other for autonomous sensor development.

Theme 5. Assessment of Socioeconomic Impacts and Development of Strategies to Conserve Marine Organisms and Ecosystems

Scientists from many Federal agencies, including DOS, NOAA, NASA, USGS, and EPA, contributed to the Intergovernmental Panel on Climate Change activities related to the sixth assessment cycle and Special Report on the Ocean and Cryosphere in a Changing Climate, both of which include consideration of OA.

The EPA worked on a review and meta-analysis of the peer-reviewed literature on the expected economic impacts of OA.

Theme 6. Education, Outreach, and Engagement Strategy on Ocean Acidification

NOAA, NSF, and NASA contributed funds to host the 5th Oceans in a High CO_2 World conference in Lima, Peru in the fall of 2020. While the conference was postponed to 2022, the commitment of the agencies remain in place.

DOS continued funding a public-private partnership with NOAA and The Ocean Foundation to expand OA monitoring in Latin America, the Caribbean, and the Pacific Islands through regional training workshops, provision of equipment kits for ocean monitoring, and ongoing mentoring. This partnership began with FY 2015 funding, with the project commencing in September 2016 and ending in October 2019. Funded activities included blue carbon restoration projects and the monitoring of the effects of restoration on local ocean chemistry.

The Ocean pH Research Integration and Collaboration in Africa program, a public-private partnership of government, civil society, and private stakeholders launched in 2016 and concluded in April 2019. Scientists from partner countries attended training workshops and received ongoing mentorship as part of the Global Ocean Acidification Observing Network's Pier-2-Peer Program, managed by NOAA. The DOS and the Swedish International Development Agency co-sponsored follow-up training for scientists who were selected to receive equipment and a stipend to monitor OA in their countries' coastal waters. Over its period of performance, this Program leveraged more than $1 million in additional funding from multiple sources to expand the program's capacity building activities.

OA remained a key issue at the fifth and sixth Our Ocean conferences in October 2018 and October 2019 respectively, at which the United States announced contributions through the International Atomic Energy Agency's Peaceful Uses Initiative to support the OA International Coordination Center.

NOAA continued to foster the activities and growth of the Global Ocean Acidification Observing Network (GOA-ON), with the NOAA OA Program Director serving as co-chair of the network. In FY 18 and 19, NOAA worked with GOA-ON to provide training workshops for international scientists. These workshops, which occurred in Monaco, Colombia, Africa, and in South Pacific Island nations, help to increase OA monitoring and research capacity across the world's oceans. The fourth GOA-ON workshop was hosted in Hangzhou, China in 2019, and focused on 1) ocean and coastal acidification in a multi-stressors environment, 2) observing ocean and coastal acidification and the impacts on organisms and ecosystems, 3) regional and global modelling on physical-biogeochemical coupling processes related to OA and the associated ecosystem responses, and 4) shaping GOA-ON to better meet the information needs of global to local decision makers. At the end of FY 2019, GOA-ON had 730 members representing

100 nations. The Pier2Peer Program, a GOA-ON mentorship program run by the NOAA OA Program, had over 100 active mentor-mentee pairs.

NOAA worked with Fisheries and Oceans Canada in FY 2018 and 2019 under their OA Collaboration Framework to advance joint activities related to OA monitoring and research, experimentation, and modelling on species response to OA.

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

Theme 7. Data Management, Integration, and Synthesis
The Ocean Carbon Data System, which was launched in August 2017 by the NOAA National Centers for Environmental Information, continued to host and provide access to ocean carbon data collected from around the world. This 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 U.S. and International ocean carbon observing programs. The effort is jointly funded by NASA and NOAA.

NOAA maintained the OA Data Stewardship project as its OA data management focal point. 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. NOAA also supports the Global Ocean Carbon Data Management and Synthesis Project to ensure consistently-formatted and quality-controlled ocean carbon measurements with well-constrained uncertainties for Earth System Model assessments, data-assimilating models, property budgets, and measurement inversions designed to address scientific questions related to ocean carbon uptake for advancing and communicating global carbon cycle science.

National

Similar to global-scale OA projects, relatively 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 Responses to Ocean Acidification
The 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.

The SI’s Marine Global Earth Observatory network, a SI coastal ocean observing initiative directed by the Tennenbaum Marine Observatories Network, adopted an ecological perspective to address the following in coastal marine ecosystems: 1) the relative magnitude of biological and physical factors driving pH variability as a function of CO_2, 2) the relationship of pH variability to biological community dynamics within a system, and 3) the generalizability of biological influences across systems. Using

spatially replicated, habitat-scale observations of pH, oxygen, physical (temperature and salinity) and biological (macrophyte composition and biomass, total suspended solids and seston composition) parameters we assessed the factors associated with short-term pH variability in seagrass and adjacent habitats across 6 temperate, subtropical and tropical sites within the Smithsonian MarineGEO network: Friday Harbor Labs, Washington with University of Washington; South Bay, Virginia with The Nature Conservancy and Virginia Institute of Marine Science; Indian River Lagoon, Florida with Smithsonian Marine Station; Aransas Bay, Texas with Texas A&M University Corpus Christi; Carrie Bow Cay, Belize with SI; Bocas del Toro, Panama with Smithsonian Tropical Research Institute. As part of the Marine Global Earth Observatory, the SI has continued its program for making continuous, *in situ* coastal water pCO_2 measurements at two of its marine science directorates combined with and weekly/biweekly total alkalinity samples/measurements. These monitoring efforts at Bocas del Toro, Panama and Smithsonian Environmental Research Center (Chesapeake Bay), Edgewater, Maryland.

USGS continued regional-scale assessments of seafloor 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, support coastal hazards risk assessments and habitat restoration planning and implementation. USGS maintains an extensive repository of coral and sediment cores and performs ongoing analytical projects to recover and interpret historical records of environmental change in coastal environments.

Theme 2. Monitoring of Ocean Chemistry and Biological Impacts

Eleven of the EPA's National Estuary Programs monitored *in situ* coastal acidification using autonomous pH and pCO_2 sensors, or began development of such monitoring programs, including Barnegat Bay Partnership, Casco Bay Estuary Partnership, Coastal Bend Bays and Estuaries Program, Long Island Sound Study, Massachusetts Bays National Estuary Program, Mobile Bay National Estuary Program, Puget Sound Partnership, San Francisco Estuary Partnership, Santa Monica Bay Restoration Commission, Tillamook Estuaries Partnership, and Tampa Bay Estuary Program. This monitoring is capturing the high-resolution data necessary to better understand the vulnerability of these estuaries to acidification impacts, the factors affecting spatial and temporal variability in acidification parameters, and the drivers responsible for changes in pCO_2 and associated acidification. The preliminary data analysis indicates that there are regional differences in the drivers of acidification, particularly the influence of coastal upwelling versus land-based freshwater sources.

The EPA initiated incorporation of a coastal acidification pilot indicator into the 2020 National Coastal Condition Assessment Survey. Total alkalinity will be measured at all 750 National Coastal Condition Assessment estuarine sites. The data will be used to establish a baseline and assess patterns in buffering against coastal acidification and model total alkalinity in estuaries.

NOAA grew the National Ocean Acidification Observation Network, which utilizes 16 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 U.S. regions on an approximately 4-year cycle, and occurred along the U.S. East Coast in summer 2018. NOAA supported long-term monitoring of biological, physical, and socioeconomic indicators throughout the U.S. Pacific, Atlantic, Gulf of Mexico, and Caribbean coral reef areas.

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

Theme 3. Improving Models of the Effects of Ocean Acidification on Ecosystems and Society
USGS supports active research and modeling to inform understanding of risk reduction and hazard mitigation services of natural seafloor infrastructure, particularly coral reefs. USGS Program objectives include integrating models of reef evolution and response to long-term forecasts of coastal risk and resilience.

Theme 4. Technology Development and Standardization of Methods
The 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 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 and NIST to standardize how pH is measured for long-term monitoring from coastal waters to open ocean.

USGS continued support of its Carbon Analytical Laboratory in St. Petersburg, Florida to provide analytical services for USGS activities and external research institutions, and informal training to external researchers. This laboratory operates under strict quality assurance and control guidelines including use of certified reference materials, performance testing and reporting, and participation in inter-laboratory comparisons.

Theme 5. Assessment of Socioeconomic Impacts and Development of Strategies to Conserve Marine Organisms and Ecosystems
The 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, Washington; Gulf of Maine).

NOAA continued funding two regional OA vulnerability assessments in the Pacific Northwest and three data-synthesis projects that will ultimately contribute to vulnerability assessments in the Northeast, mid-Atlantic, and Hawaiian Islands. These projects will provide actionable information for marine resource decision makers. NOAA also supported four projects related to the societal consequences of ecological systems crossing thresholds due to OA. These projects focus on Gulf of Alaska salmon, water quality and shellfish in the Northeast, aquaculture and wild oysters in the Chesapeake Bay, and seagrass and oysters in the mid-Atlantic.

USGS supports active research and modeling to inform understanding of risk reduction and hazard mitigation services of natural seafloor infrastructure, particularly coral reefs. USGS Program objectives

include integrating models of reef evolution and response to long-term forecasts of coastal risk and resilience.

Theme 6. Education, Outreach, and Engagement Strategy on Ocean Acidification
In February 2018, 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. By the end of FY 2019, the site had 820 members and robust contribution by the OA community.

NSF and NASA provided support for the Ocean Carbon and Biogeochemistry Project Office. The Ocean Carbon and Biogeochemistry Project supports community planning activities for OA and carbon cycling and OA research (and related activities), and engages in public outreach activities. With NSF support, the Ocean Carbon and Biogeochemistry Project Office provided support for the "Ocean-Atmosphere Interactions: Scoping Directions for New Research" that took place in October, 2019. The workshop's aim was to advance science and strengthen collaboration in the air-sea research community, a relevant topic for ocean acidification.

The EPA continued to update its public-facing website for ocean and coastal acidification which includes basic information, causes and effects of OA, the EPA's activities, and what the public can do to assist these efforts. The EPA continued to evaluate ways to improve coastal acidification outreach and communication, and presented research activities and findings to stakeholders and the public. The EPA continued to provide training on coastal acidification monitoring and research to undergraduate and post-graduate students (through the Oak Ridge Institute for Science and Education/Oak Ridge Associated Universities, Sea Grant and American Association for the Advancement of Science internship programs).

NOAA staff engaged in a variety of OA-related education, outreach, and engagement activities in addition to a number of NOAA websites and social media accounts highlighting OA. NOAA also trained many undergraduate and graduate students in OA research methodologies through a variety of internship and fellowship programs. NOAA offices developed summaries and explanations of OA and related science efforts for communication platforms such as NOAA's "Science on a Sphere" and "Data in the Classroom." NOAA continued the Sharing OA Resources for Communicators and Educators webinar series, which has reached over 1,750 participants to date.

NOAA continued its OA Education MiniGrant program. The awardees are working to develop OA curricula, educational multi-media tools, and citizen-science programs on the Mid-Atlantic, Southeast, West, and Caribbean and Pacific Island coasts of the United States. NOAA mentored a number of students in the development of OA education and communication toolkits. The NOAA Bay Watershed Education and Training, which provides meaningful watershed educational experiences for students and related professional development for teachers, funded 12 projects in 2018 and 19 projects in 2019 around the country which included an OA component.

NOAA Sea Grant and state Sea Grant offices raised awareness about OA through education and extension efforts.

The NPS continued building its Ocean Acidification Toolkit for parks by creating: a national-level brochure on OA; an internal website with summaries of all the current OA work occurring in the national parks which includes links to scientific journal articles, other websites, and science summaries of all the science going on in NPS park units; an interpretive script and presentation template that describes OA and can be modified for use at any park; a social media package designed to help educate the public on the topic of OA that includes pictures or park resources, posts, and links to websites; a photo database of pictures from NPS park units in the Pacific Northwest; and a junior ranger booklet dedicated to the topic of OA, which was designed by an artist.

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 and stakeholder presentations, websites, and a monthly USGS newsletter *Soundwaves*. USGS continues engagement with the Southeast Ocean and Coastal Acidification Network, Gulf of Mexico Coastal Acidification Network, and as a member of the Ocean Acidification Information Exchange steering committee. USGS is committed to developing more effective methods and partnerships to ensure USGS science is delivered effectively to policy and decision makers.

Theme 7. Data Management, Integration, and Synthesis
The EPA developed a report that compiles data and lessons learned from the National Estuary Program sites conducting *in situ* coastal acidification monitoring using autonomous pH and pCO_2 sensors. The EPA began the development of guidelines for data management, data archiving and data sharing on public platforms for coastal acidification monitoring data collected by the National Estuary Programs and citizen science groups.

The Biological and Chemical Oceanography Data Management Office handles data management for the NSF Biological and Chemical Oceanography Programs, as well some previous NSF-wide activities such as Science, Engineering and Education for Sustainability Investment: Ocean Acidification. This Data Management Office transfers oceanographic data to NOAA for permanent archival.

Theme 8. Other research and monitoring activities
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.

United States Northeast

Theme 1. Research to Understand Responses to Ocean Acidification
The 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. The EPA also continued its study of coastal acidification impacts on shellfish in Narragansett Bay, Rhode Island.

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. These labs conducted OA research on Eastern oysters, Atlantic surfclams, Atlantic sea scallops, blue mussels, American horseshoe crab, summer flounder, Atlantic silverside. Through its Saltonstall-Kennedy grant program, NOAA funded the Bigelow Laboratory for Ocean Sciences to study how kelp affects OA conditions in Maine. New York Sea Grant funded projects to 1) quantify the ability of seagrass to draw down pCO_2 from the water and determine the extent that this seagrass-modified water can ameliorate the negative impacts of OA on juvenile shellfish in the laboratory and in nature and 2) determine effective mitigation and adaptation measures for lessening the impacts of climate change and OA on economically important shellfish (Stony Brook University). Maine Sea Grant supported a project to quantify modern and pre-anthropogenic pH baselines and variability, studying the impact of pH variability on commercially-relevant shellfish, and communicating results to stakeholders (Claremont McKenna College). MIT Sea Grant funded projects to promote literacy and hands-on opportunities for coastal populations related to climate change adaption (MIT), determine the potential impact of OA on aquaculture practices of the Eastern oyster (University of Massachusetts), measure how the internal chemistry of New England's commercial important molluscs respond to OA and climate change (Northeastern University), investigate the effects of OA and warming on the calcification rate and shell properties of early life stages of commercially important New England molluscs (Northeastern University), quantify coastal OA impacts on estuarine nitrogen removal (Boston University), characterize the impact of multiple climate stressors on American lobsters (University of Massachusetts), and quantify the contribution of wastewater effluent to coastal acidification and develop sensors for measuring OA (Woods Hole Oceanographic Institution). Connecticut Sea Grant funded projects to predict the performance of a copepod under warming and OA (University of Connecticut),

Acadia National Park and the Schoodic Institute are partnering with Cedar Crest College to continue work on understanding the role of OA and warming on intertidal community assemblages, focused largely on upper intertidal algae. This project, which incorporates citizen science, is expected to continue as a long-term study into the impacts of OA on the Acadia National Park intertidal ecosystem.

Theme 2. Monitoring of Ocean Chemistry and Biological Impacts

The 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. The EPA conducted coastal plankton incubation experiments examining the effects of nutrient enrichment on pH and dissolved inorganic carbon speciation.

Coastal acidification *in situ* monitoring continued at EPA's National Estuary Program sites in Casco Bay (Maine), Mass Bays (Massachusetts) and Long Island Sound (New York and Connecticut) using pH and pCO_2 autonomous sensors. The monitoring in Casco Bay and Long Island Sound began in 2015 and 2016 and the data will help establish baseline data and to understand vulnerability of these coastal waters to coastal acidification.

The EPA increased the technical monitoring capacity of citizen scientists monitoring coastal acidification in the Northeast by supporting Shell Day, a single-day monitoring event along the coast from Long Island Sound to Downeast Maine. During this event, water quality monitoring groups took

temperature, salinity, and pH measurements and collected water samples during low, mid, and high tides. The collected water samples were analyzed by a number of partnered laboratories to determine the total alkalinity and its relationship to salinity. Shell Day is a multiagency and academic citizen science project supported by Northeast Coastal Acidification Network, the EPA, NOAA, and state agencies.

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 the summer of 2018, NOAA conducted a synoptic OA-focused cruise of the U.S. East Coast from Nova Scotia to mid-Florida. NOAA funded carbon chemistry sampling during six Northeast Fisheries Science Center's Ecological Monitoring cruises. To better design the OA observing system for the Northeast and Mid-Atlantic regions, NOAA funded two observing system optimization projects. One will deploy autonomous underwater gliders with pH and other sensors and apply these data to an existing ocean ecosystem/biogeochemical model that resolves carbonate chemistry and its variability. The second will develop a regionally downscaled projection for the Northeast, evaluate the ability of the existing observational network to detect changes in OA-relevant stressors for scallops, and propose a process-based strategy for the observing network moving forward. Similarly, MIT Sea Grant funded a project that aims to design a cost-effective and robust OA monitoring system in the Northeast based on theory, measurements, and simulation.

Assateague National Seashore and other national parks in the Northeast and mid-Atlantic regions contributed to NOAA's East Coast synoptic OA survey in 2018 by collecting nearshore samples to correspond with NOAA's offshore sampling. Acadia National Park deployed an autonomous SeapHOx from February 2019-20 which measured pH, salinity, dissolved oxygen, temperature. The NPS Northeast Coastal and Barrier Inventory and Monitoring Network continues to conduct seagrass monitoring and water quality measures annually or bi-annually (e.g., dissolved oxygen, temperature, salinity, chlorophyll a, light attenuation, turbidity, pH) at many parks from Massachusetts to Virginia.

The Pioneer Array, an element of NSF's Ocean Observatories Initiative located between central New Jersey and Martha's Vineyard, Massachusetts, continues to provide 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, and for the Northeast U.S. Shelf LTER, focused on shelf waters of the Middle Atlantic Bight and Gulf of Maine and linked to the Ocean Observatories Initiative Pioneer Array.

Theme 3. Improving Models of the Effects of Ocean Acidification on Ecosystems and Society
The EPA conducted research to predict responses of estuarine production and carbonate chemistry to nutrient loading using stable carbon isotopes.

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.

NOAA funded a project that expands the existing Northeast Coastal Ocean Forecast System to develop OA detection and warning systems for coastal water quality and shellfish/aquaculture managers. NOAA also funded a data synthesis effort to look at long-term trends in water quality data to identify the key drivers of OA in Maine's 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. With the University of Maryland and Louisiana State University, NOAA used life-cycle modeling to study how OA may influence winter flounder populations.

Theme 4. Technology Development and Standardization of Methods
The EPA continued investigating low-cost alternatives for handling and analysis of seawater OA samples.

MIT Sea Grant funded development of miniaturized *in situ* sensor technologies that can simultaneously measure seawater dissolved inorganic carbon and pCO_2 (MIT).

Theme 5. Assessment of Socioeconomic Impacts and Development of Strategies to Conserve Marine Organisms and Ecosystems
The 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. The EPA funded the *Ocean to Plate to Ocean* shell collection study in Casco Bay, Maine that tests the impact of shell material deposition on pH and shellfish recruitment in tidal flats. Activities focused on evaluating approaches to experimentally deploy crushed shells on clam flats.

Theme 6. Education, Outreach, and Engagement Strategy on Ocean Acidification
The Northeast Coastal Acidification Network is a joint Federal, academic, and industry partnership established under the Northeast Regional Association of Coastal and Ocean Observing Systems, and is supported by EPA and NOAA. The Network led the synthesis and dissemination of regional ocean and coastal acidification data and information from Long Island Sound to the Scotian Shelf through workshops, web development, and other efforts. It provided 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, and coordinates and develops regional priorities for science observing and research investments designed to further understanding of OA.

The EPA conducted a project to assist a network of participatory scientists to measure coastal acidification variability in estuaries in New England by providing high quality, and more affordable, new technology to citizen scientist organizations. Organizations will measure pH and collect water samples for total alkalinity to help estimate levels of carbonate saturation in coastal waters.

NOAA funded a project that is cross-calibrating citizen science monitoring protocols for OA among independent organizations in the Northeast by developing a replicable citizen science monitoring training program.

United States Mid-Atlantic

Theme 1. Research to Understand Responses to Ocean Acidification

Combining field measurements and laboratory incubations, the SI (through the Smithsonian Environmental Research Center) investigated and quantified ecosystem metabolism to better understand the biological contributions to CO_2 in estuarine habitats in Chesapeake Bay. The Marine Global Earth Observatory network coordinated measurement of carbonate and non-carbonate chemistry parameters to investigate the correlation of pH variability with benthic and water column biological productivity in Chesapeake Bay.

Virginia Sea Grant funded projects on the carry-over effects of environmental pH and temperature on Eastern oysters and the influence of salinity history on future OA tolerance in larval Eastern oysters (Virginia Institute of Marine Science). Maryland Sea Grant funded a project focused to understand how resiliency of juvenile oysters to estuarine stressors, including coastal acidification, and climate change, may influence restoration and aquaculture programs (Smithsonian Environmental Research Center).

Theme 2. Monitoring of Ocean Chemistry and Biological Impacts

BOEM, NOAA, and USGS collaborated on a study of deep-sea coral, canyon, and gas seep ecosystems in the mid- and south Atlantic. The study includes characterization of water column carbonate chemistry in addition to many other measurements of water column and sediment biogeochemistry and geomorphology. The overarching goal for this project is to augment the ability to predict the location of seafloor communities within the study area that are potentially sensitive to natural and anthropogenic disturbances.

Coastal acidification *in situ* monitoring continued at EPA's National Estuary Program sites in Barnegat Bay, New Jersey using pH and pCO_2 autonomous sensors. This monitoring began in 2016 to help establish baseline data and to understand vulnerability of these coastal waters to coastal acidification. The EPA continued to participate in Mid-Atlantic Regional Ocean Council, specifically the monitoring work group to develop a 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 the EPA and other Federal agencies and collaborating Mid-Atlantic States.

NOAA initiated operating an OA mooring at the mouth of the Chesapeake Bay in April 2018 at First Landing. In the summer of 2018, NOAA conducted a synoptic OA-focused cruise of the U.S. East Coast from Nova Scotia to mid-Florida that extended from the coast out to the shelf break. NOAA funded carbon chemistry sampling during six Northeast Fisheries Science Center's Ecological Monitoring cruises and provided extensive surface monitoring coverage by means of surface pCO_2 underway autonomous systems installed on several NOAA vessels and volunteer observing ships. Delaware Sea Grant funded the addition of pH and CO_2 sensors on the Cape May-Lewes Ferry.

NSF provided ongoing support for the Virginia Coastal Reserve LTER. The site collects time series data on carbon and nutrient cycling, biological communities, pH, and estuarine carbonate chemistry.

Theme 3. Improving Models of the Effects of Ocean Acidification on Ecosystems and Society

NOAA funded a modeling project focused on whether meadows of underwater eelgrass can mitigate the harmful effects of OA on Eastern oysters. 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. 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 NOAA-supported synoptic OA cruises in the regions.

SI funded development of a correlative model that incorporates biological forcing and ecosystem metabolism, and non-carbonate, environmental measurements to model/predict pCO_2 levels.

Theme 4. Technology Development and Standardization of Methods
To address the robustness and reliability limitations of automated instrumentation for making pCO_2 measurements in highly turbid and productive estuaries, SI (through the Smithsonian Environmental Research Center) supported research and development of a spherical falling film gas-liquid equilibrator of CO_2 and other trace gases.

Theme 5. Assessment of Socioeconomic Impacts and Development of Strategies to Conserve Marine Organisms and Ecosystems
A NOAA-funded modeling project focused on the Chesapeake Bay is bridging the gap between scientific knowledge and current management needs by building better understanding of the drivers of OA, identifying shellfish restoration areas most and least prone to acidification impacts, and understanding feedbacks associated with future environmental conditions and shellfish restoration goals.

Theme 6. Education, Outreach, and Engagement Strategy on Ocean Acidification
EPA and NOAA continued supporting operations of and participating in the Mid-Atlantic Ocean Acidification Network (MACAN). 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. It 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, and 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. MACAN hosted eight webinars to develop the state of the science and share scientific findings with interested academics and stakeholders. MACAN hosted its second workshop in May 2019 with the objectives of identifying stakeholder concerns and associated information needs, prioritizing a plan for working through gaps, providing an update on the Industry Stakeholder Outreach Survey, and mapping out various areas currently being worked on by members to identify potential collaborations and opportunities to fill knowledge gaps. MACAN published strategy documents focused on research priorities for ecological impacts and OA monitoring in the region.

NOAA, Virginia Sea Grant, Delaware Sea Grant, New York Sea Grant, New Jersey Sea Grant Consortium, and the National Sea Grant College Program supported 6 students through the Mid-Atlantic Ocean, Coastal, and Estuarine Acidification Graduate Research Fellowship, which included a week-long, interdisciplinary training program.

United States Southeast and Gulf Coast

Theme 1. Research to Understand Responses to Ocean Acidification

USGS continued field experiments in collaboration with EPA using natural gradients and best practice methods to examine controls on coastal acidification in Tampa Bay, Florida and potential for habitat restoration to mitigate its impacts. USGS is currently investigating the rate and processes of microbially mediated carbonate sediment dissolution and precipitation of carbonate seafloor sediments in Tampa Bay with potential expansion to other coastal environments. USGS performed field activities in the Florida Keys to locate and map mangrove coral habitats that may be serving as a refuge for reef building corals from climate change and coastal acidification.

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

Georgia Sea Grant funded a study to characterize the sensitivity of Gray's Reef invertebrates and algae to OA and understand the implications of OA for the ecosystem (University of Georgia). NOAA supported field-based research activities in Florida, the U.S. Virgin Islands, and Puerto Rico to characterize physical and chemical changes in coral reef ecosystems with enhanced question-based monitoring and to understand the response of coral growth and calcification across natural gradients in CO_2.

NSF funded a study on the interplay of sediment geochemistry and ocean acidification in the northern Gulf of Mexico. In the aftermath of Hurricane Harvey, NSF supported a RAPID response grant to a team of researchers already investigating the carbon cycle and controls on pH in the northern Gulf, adding field work to document the effects of the hurricane and associated freshwater inputs.

SI's Marine Global Earth Observatory coordinated measurement of carbonate and non-carbonate chemistry parameters to investigate the correlation of pH variability with benthic and water column biological productivity in Indian River Lagoon, Florida with Smithsonian Marine Station and Aransas Bay, Texas with Texas A&M University Corpus Christi, Texas.

Theme 2. Monitoring of Ocean Chemistry and Biological Impacts

BOEM, 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 South Florida and Caribbean Inventory and Monitoring Network helped collect total alkalinity and dissolved inorganic carbon surface water samples every other year inside and outside Florida and Caribbean park waters as part of the NOAA coral reef water chemistry program. USGS continued collaboration with NPS to monitor calcification rates in coral reefs in Dry Tortugas National Park,

Biscayne National Park, and in the Florida Keys National Marine Sanctuary. The goal of this work is to establish baseline calcification rates for corals and calcareous algae and determine how they respond to environmental change.

Coastal acidification *in situ* monitoring continued at EPA's National Estuary Program sites in Coastal Bends Bay National Estuary Program (Texas) and Tampa Bay Estuary Program (Florida) using pH and pCO_2 autonomous sensors. This monitoring began in 2016 and 2017 and the data will help establish baseline data to understand vulnerability of coastal waters to coastal acidification. A new coastal acidification monitoring program began the planning stages in the Mobile Bay National Estuary Program.

In the summer of 2018, NOAA conducted a synoptic OA-focused cruise of the U.S. East Coast from Nova Scotia to mid-Florida. NOAA operated a mooring at the Gray's Reef, off of Georgia, and collected underway pCO_2 data and bulk water samples in the area around the mooring four times a year. It also operated an OA mooring at Cheeca Rocks, Florida. NOAA monitored the progression and impacts of OA at a number of coral reef sites, including Florida Keys, Dry Tortugas, and Flower Garden Banks. Puerto Rico Sea Grant funded the first assessment of the spatial variability of the carbonate chemistry and hydrodynamic conditions across different habitat components of La Parguera coastal barrier, which identified the areas of particular vulnerability to dissolution due to OA (University of New Hampshire).

NSF provided ongoing support for the Georgia Coastal Ecosystem LTER. The site collects 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. Improving Models of the Effects of Ocean Acidification on Ecosystems and Society
The EPA scientists continued developing biogeochemical models and conducting field studies to parameterize these models for use in explaining the impacts of nutrients in coastal ecosystems.

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 continued climate vulnerability assessments for Gulf of Mexico and South Atlantic commercially harvested and protected species and habitats.

Theme 6. Education, Outreach, and Engagement Strategy on Ocean Acidification

NOAA and NSF funded Research Experience for Undergraduates sites at Texas A&M University, Mote Marine Laboratory, and the Louisiana Universities Marine Consortium, all of which include a focus on OA research.

NOAA along with the Southeast and Gulf of Mexico Coastal Ocean Observing System Regional Associations continued supporting two regional coastal acidification networks, the Southeast Ocean and Coastal Acidification Network and the Gulf of Mexico Coastal Acidification Network respectively. Each network includes Federal and state agency representatives, resource managers, industry partners, and research scientists, and works to facilitate monitoring, research, and collaboration to address coastal and ocean acidification impacts. The Southeast Ocean and Coastal Acidification Network hosted two stakeholder workshops, one focused on South Carolina and Georgia and the other on North Carolina. The Gulf of Mexico Coastal Acidification Network hosted multiple webinars in FY 2019.

USGS continues engagement with the Southeast Ocean and Coastal Acidification Network, Gulf of Mexico Coastal Acidification Network, and as a member of the Ocean Acidification Information Exchange steering committee. USGS is committed to developing more effective methods and partnerships to ensure our science is delivered effectively to policy and decision makers.

Theme 8. Other research and monitoring activities
NSF provided funding to the University of Florida to install a modular seawater delivery and filtration system for a new mesocosm facility at the Nature Coast Biological Station. This system will augment the station's ability to facilitate interdisciplinary ecological research, including studies on the response of plants and animals to OA, warming temperatures, changing seasonality, and freshwater discharge.

Caribbean

Theme 1. Research to Understand Responses to Ocean Acidification
EPA scientists studied the calcification in Caribbean reef-building corals at high pCO_2 levels in a laboratory-based recirculating ocean acidification exposure system.

NOAA conducted experiments using molecular tools to characterize the resilience of coral reefs to OA and warming and to understand how OA conditions influence the actions of Caribbean microborers on coral erosion, including assessing differences in day and night-time dissolution.

SI scientists took coordinated measurement of carbonate and non-carbonate chemistry parameters to investigate the correlation of pH variability with benthic and water column biological productivity at the Marine Global Earth Observatory site in Carrie Bow Cay, Belize.

Theme 2. Monitoring of Ocean Chemistry and Biological Impacts
NOAA 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 a mooring for OA at La Parguera, Puerto Rico. 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).

The USGS initiated monitoring of calcification rates in coral reefs in Buck Island Reef National Monument, U.S. Virgin Islands. The goal of this work is to establish baseline calcification rates for corals and calcareous algae and determine how they respond to environmental change.

Theme 3. Improving Models of the Effects of Ocean Acidification on Ecosystems and Society
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. NOAA also supported a synthesis of NOAA-collected OA observations at coral reefs in order to better understand reef-scale biogeochemical processes and better link projection models of oceanic carbonate systems to reef-scale OA impacts.

SI developed a correlative model that incorporates biological forcing and ecosystem metabolism, and non-carbonate, environmental measurements to model/predict pCO_2 levels.

Theme 6. Education, Outreach, and Engagement Strategy on Ocean Acidification
NOAA funded the development of a Spanish and English language video on OA and its implications for Puerto Rican local resources and economy, which will be shown at visitor centers.

United States West Coast

Theme 1. Research to Understand Responses to Ocean Acidification
BIA funded the Suquamish Indian Tribe to work with NOAA, Puget Sound Restoration Fund, and Washington Department of Fish and Wildlife on basket cockles to better understand their sensitivity to OA and status within Puget Sound, information needed to develop potential restoration and resilience management strategies.

The EPA conducted 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 and macroalgae in moderating acidification.

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, Washington). NOAA scientists studied Dungeness crab, coho and Chinook salmon, sablefish, pteropods, geoduck, and krill under OA conditions, often conducting OA experiments with stressors expected to co-occur with OA (high temperature, low oxygen).

Washington Sea Grant funded the University of Washington to investigate the effects of OA on salmon and sablefish olfactory neurobehavioral function and salmon geomagnetic neurobehavioral function, how zooplankton and ichthyoplankton communities respond to water carbonate chemistry in Puget Sound, the impacts of OA on wild and farmed mussels in Puget Sound, and the interaction between eelgrass, oysters, the pathogen that causes eelgrass wasting disease, and the expression of the disease under different environmental conditions including carbonate chemistry. Oregon Sea Grant funded the University of Oregon to study the effects of OA on the behavior, development, and nutritional value of Dungeness crab and Oregon State University to examine lethal and sub-lethal effects of OA and warming on early-life stage pink shrimp, how vulnerable or resilient the life-stages of native shellfish

are to OA and low oxygen, and practices for shell planting and oyster culture that mitigate OA impacts. California Sea Grant supported projects to study if restoring kelp forest habitat buffers seawater carbonate chemistry (University of California Davis), determine the effect of OA and low oxygen on pregnant female rockfish (University of California Santa Cruz), develop an experimental co-culture system where shellfish can be grown together with seaweed with the goal of mitigating the impacts of OA (Moss Landing Marine Laboratory), quantify the ecosystem services including carbon absorption of aquaculture of a native seaweed species (University of California Berkeley), and understand the drivers of hypoxia and OA conditions in shallow coastal locations in central California (California Polytechnic State University).

NOAA researchers continued work on a project funded by the Paul Allen Foundation 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.

SI Marine Global Earth Observatory coordinated measurement of carbonate and non-carbonate chemistry parameters to investigate the correlation of pH variability with benthic and water column biological productivity in SI Marine Global Earth Observatory site in Friday Harbor Labs, Washington with University of Washington.

Theme 2. Monitoring of Ocean Chemistry and Biological Impacts

The IWG-OA and Pacific Coast Collaborative continued working together via 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 are being used for gap analysis efforts to inform monitoring investments.

BIA funded the Jamestown S'Klallam Tribe to monitor OA near tribal shellfish aquaculture and shellfish harvest beaches to identify natural variability, investigate long-term trends, and assess future vulnerability to OA; the Quileute Indian Tribe to identifying monitoring protocols and critical indicator species/environmental parameters needed to inform management of marine resources under changing ocean conditions such as OA; and the Northwest Indian Fisheries Commission to increase of OA monitoring capacity.

Coastal acidification monitoring continued at EPA's National Estuary Program sites in San Francisco Bay, California; Santa Monica Bay, California; and Tillamook Bay, Oregon using *in situ* pH and pCO_2 autonomous sensors. This monitoring began in 2017 and 2018 and will help establish baseline data to understand vulnerability of coastal waters to coastal acidification. In Puget Sound (Washington) and Tillamook Bay, EPA examined how watershed activities interacts with natural events to exacerbate the magnitude and duration of coastal acidification and hypoxia in these estuarine habitats. EPA continued monitoring of carbonate chemistry in Tillamook Estuary in collaboration with Tillamook Estuaries Partnership.

NOAA continued analyzing samples and data from the 2016 synoptic OA cruise of the West Coast. 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 an open-ocean OA moorings off Southern California. NOAA also conducted regular OA-related monitoring at the Olympic Coast National Marine Sanctuary (Washington). NOAA maintains underway CO_2 systems on the NOAA ships *Oscar Dyson* and *Bell M. Shimada*, which operate in the continental shelf regions of Alaska, Washington, Oregon, and California

NOAA and IOOS supported OA monitoring at shellfish aquaculture sites along the West Coast, meeting industry's information needs while also gathering data on how OA is expressed in nearshore waters. NOAA's Cordell Bank and Greater Farallones National Marine Sanctuaries (California), working with Point Blue Conservation Science and University California Davis, characterized carbonate chemistry conditions in the two sanctuaries.

NPS continued monitoring OA (pH, total alkalinity) at Olympic National Park, San Juan Islands National Historical Park, Cabrillo National Monument and Channel Islands National Park and monitored intertidal biota as part of the NPS Inventory and Monitoring program, data which could be used to detect biological impacts of OA via changes in community structure.

The Coastal Endurance Array, an element of NSF's Ocean Observatories Initiative, is located off the coast of Oregon and Washington and collects measurements relevant to studies of OA. NSF continued to support the Santa Barbara Coastal LTER site, with contributing support for OA-related measurements, and OA-related observations and ship time at the California Current Ecosystem LTER site. A new project focused on the effects of ocean acidification on iron bioavailability and uptake by phytoplankton in coastal and open ocean waters of the eastern North Pacific.

Theme 3. Improving Models of the Effects of Ocean Acidification on Ecosystems and Society

The EPA continued to support the use of the Salish Sea model that examines how regional freshwater/land-derived sources of nutrients impact acidification. This model was completed through a partnership between the EPA, Washington Department of Ecology, and Pacific Northwest National Laboratory. 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.

NOAA funded two modeling projects in the California Current region: (1) a model to predict spatially explicit current carbon chemistry conditions from the limited available measurements (Oregon State University) and (2) a model to generate seasonal forecasts of ocean carbonate chemistry and other conditions in the Pacific Northwest (University of Washington). The latter model 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. 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. NOAA's Cordell Bank and Greater Farallones National Marine Sanctuaries (California) worked with Point Blue Conservation Science and University California Davis to develop a region-specific OA model and determine biological impacts of OA.

Theme 4. Technology Development and Standardization of Methods
IOOS and NOAA supported OA sensor development and application, targeting shellfish industries across the United States West Coast, Alaska, and Hawaii. 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
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 projects to assess the socio-cultural vulnerability and resilience of tribal and non-tribal coastal communities to OA in Washington (University of Washington) and understand the vulnerability and adaptation to OA among Pacific Northwest mussel and oyster stakeholders (Oregon State University). 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. In addition, NOAA funding assisted in the development of an OA-tolerant abalone strain.

The Olympic Coast National Marine Sanctuary was designated as an "OA sentinel site, " serving as a place where government, academic and citizen scientists work collectively and share information on sanctuary conditions and emerging threats, including OA. NOAA completed the salmon-focused portion of the West Coast Climate Vulnerability Assessment that examines the vulnerability of 33 salmon population segments in the region to climate change, including OA. It continued work on the assessment of 65 West Coast fish stocks. These assessments are linked to NOAA Fisheries Social Indicators to examine the climate vulnerability of West Coast coastal communities.

NOAA scientists serve as members of the California Ocean Acidification and Hypoxia Task Force, which provides scientific guidance to the California Ocean Protection Council to inform continued actions on OA and hypoxia in California and along the West Coast. NOAA scientists also serve as members of Washington's Marine Resources Advisory Committee, the body which maintains a sustainable and coordinated focus on OA.

Theme 6. Education, Outreach, and Engagement Strategy on Ocean Acidification
The California Current Acidification Network continued to create a community of OA stakeholders along the United States West Coast, hosting nine webinars.

EPA participated on the Oregon Ocean Acidification and Hypoxia (OAH) Monitoring group (formed as part of the Oregon Coordinating Council on Ocean Acidification and Hypoxia), developing plans for acidification monitoring and coordinating monitoring by state and Federal agencies.

NOAA continued support to 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'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. The NOAA Pacific Northwest and California Bay Watershed Education and Training programs funded 12 projects in 2018 and 18 projects in 2019 that included an ocean acidification component. NOAA and 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.

NPS Cabrillo National Monument prepared a film to educate the public about OA.

Theme 7. Data Management, Integration, and Synthesis
IOOS continued operating 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 Responses to Ocean Acidification
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, Arctic cod, red king crab, blue king crab, golden king crab, snow crab, and southern Tanner crab. Alaska Sea Grant funded projects to determine how OA and warming will impact the growth and metabolism of northern spot shrimps (University of Alaska Southeast) and the physiological responses of juvenile basket cockles and littleneck clams to OA (University of Alaska, Fairbanks).

NSF funded two studies on ecosystem impacts of ocean acidification in southeast Alaska, one focused on high latitude kelp forests and the other on rocky tidal ecosystems.

Theme 2. Monitoring of Ocean Chemistry and Biological Impacts
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 2019 Distributed Biological Observatory cruise collected over 600 samples along 5 of the 8 hot spots in the Bering and Chukchi Seas, as well as other hydrographic lines in the Northern Chukchi, and a series along Ledyard Bay for dissolved inorganic carbon and total alkalinity analysis.

BOEM continued funding 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 National Environmental Policy Act documents for lease sales, as well as exploration and development plans.

NOAA continued to operate two coastal OA moorings in the Gulf of Alaska located in critical fishing areas. The region has been targeted by volunteer observing ships and autonomous underwater vehicles for other monitoring and process-based work throughout 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 worked with Canadian and Alaskan partners to operate an OA monitoring system on the M/V *Columbia* passenger ferry, which takes weekly runs from Washington State to Alaska. NOAA also analyzed samples collected by Alaska Native tribes in Kodiak, an effort to better understand OA conditions in nearshore water. Analysis continued from the 2015 Gulf of Alaska synoptic OA 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.

During FY 2019, NOAA demonstrated the operational use of Saildrones, autonomous wind-and-solar-powered vehicles, by sending 6 drones from Dutch Harbor through Bering Strait to the Chukchi Seas. The Saildrone mission targeted the sea ice edge, allowing for the investigation of how carbon dioxide concentrations change close to the sea ice, and was calibrated against underway pCO_2 sensors on the USCGC *Healy.* This deployment assessed the relationship between CO_2 fluxes and respiration that place critical controls on the duration and persistence of OA events in Arctic systems.

The NPS started a project to develop a lower trophic community characterization reference condition correlated to OA parameters to initiate incorporation of lower trophic biology-OA correlations into existing long-term monitoring of Arctic lagoon communities in the Northwest Alaska. The biology reference assessment is based on flow-cytometry and characterizes the planktonic communities for community structure, size, and prevalence of structural anomalies. OA sampling is collected in conjunction with existing water quality monitoring efforts.

NSF continued funding of the Northern Gulf of Alaska LTER site that extends long-term data observations at this location, including characterization of the ocean carbon cycle and biota.

Theme 3. Improving Models of the Effects of Ocean Acidification on Ecosystems and Society
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. This work also explores the consequences of different crab management strategies.

Theme 5. Assessment of Socioeconomic Impacts and Development of Strategies to Conserve Marine Organisms and Ecosystems
NOAA supported an interdisciplinary project focused on Alaska salmon that developed integrated human-ecological models to simulate management scenarios and assess the benefits of pre-emptive adaptation planning and policy making. The output from these models is being used to create decision tools for salmon managers. NOAA completed 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 assessment was linked to NOAA Fisheries Social Indicators to examine the climate vulnerability of coastal communities.

Theme 6. Education, Outreach, and Engagement Strategy on Ocean Acidification
NOAA supported the Alaska OA Network, which 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 shared information at the Pacific Marine Expo, the largest commercial marine trade show on the West Coast, organizing presentations on OA and its effects on marine resources in FY 2018 and 2019 and manning a booth in FY 2018. The Network also hosted a number of roundtables and presentations for interested stakeholders around Alaska, assembled kits to help educators teach about OA, convened researchers working on OA in Alaska to coordinate and prioritize efforts, and conducted a stakeholder survey to better understand information needs and interests related to OA in Alaska.

Theme 8. Other research and monitoring activities
NSF provided funding to the University of Alaska, Fairbanks for facilities and instrumentation upgrades at the Kasitsna Bay Laboratory located on Kachemak Bay in south-central Alaska.

United States Pacific Islands

Theme 1. Research to Understand Responses to Ocean Acidification
In 2019, NASA concluded the Coral Reef Airborne Laboratory project, which had the overarching science goal of elucidating the relationship between coral reef condition and the various biogeophysical forcing parameters widely considered to impact reefs. This project used airborne imaging spectroscopy to make high-density observations of reef condition in areas that included Hawaii, the Mariana Islands, and Palau. The resulting data were analyzed against a suite of biogeophysical forcings. All airborne data and data products and in-water validation data are freely available online.

NOAA supported research on the impact of warming 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 also conducted laboratory-based response experiments to examine impacts of OA on the biodiversity of cryptic reef organisms and to understand how OA conditions influence the erosion activities of a boring mussel on coral structures. Hawaii Sea Grant funded projects to better understand CO_2 variation in coral reefs (University of Hawaii Manoa) and gene expression of oysters under warming conditions and OA (University of Hawaii Hilo).

NSF funded a study on Hawaiian corals, using information from the cellular to organismal level to identify key mechanisms of adaptation and acclimatization to environmental stress, including ocean acidification. Another project examines the effects of ocean acidification on the mutualistic interaction between clownfish and sea anemones in the reef systems of Papua New Guinea. A project examines the susceptibility of deep-sea corals to ocean acidification in the Northwestern Hawaiian Islands and Emperor Seamount Chain. NSF also funded a project focused on the effects of submarine groundwater discharge on coral reefs at the Mo'orea LTER site.

USGS initiated field experiments and monitoring exercises to determine the potential impact of groundwater and nutrients on coral reefs along the coastline of Tutuila, American Samoa. USGS continued collaboration with State agencies and the NPS to examine the impact of groundwater and nutrients on coral reef health and degradation in Maui, Hawaii.

Theme 2. Monitoring of Ocean Chemistry and Biological Impacts

NOAA and Hawaii Sea Grant operated four coral-reef OA moorings off Oahu, Hawaii. NOAA also operated open-ocean OA moorings off Hawaii and off Japan in the Kuroshio Extension current. In FY 2018, a new mooring was installed in Fagatele Bay, American Samoa. NOAA 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 2018 and FY 2019, NOAA monitored the progression of OA at a number of coral reef sites around the Pacific Ocean, including the Hawaiian archipelago, Pacific Remote Island Areas (Howland, Baker, Jarvis, Kingman, and Palmyra), and American Samoa (Swains, Tutuila, Ofu & Olosega, Ta'u, and Rose).

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

Theme 3. Improving Models of the Effects of Ocean Acidification on Ecosystems and Society
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. NOAA also supported a synthesis of NOAA-collected OA observations at coral reefs in order to better understand reef-scale biogeochemical processes and better link projection models of oceanic carbonate systems to reef-scale OA impacts. 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 Methods
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 is ongoing in Kaneohe Bay, Hawaii.

Theme 5. Assessment of Socioeconomic Impacts and Development of Strategies to Conserve Marine Organisms and Ecosystems
NOAA funded and hosted a workshop to discuss management strategies with Hawaiian managers, decision makers, and stakeholders to understand how different types of information related to OA could inform decisions and trigger alternative actions.

Theme 6. Education, Outreach, and Engagement Strategy on Ocean Acidification
A NOAA and National Marine Sanctuary Foundation 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 National Marine Sanctuary Foundation also funded a program in which students from American Samoa learned about climate change and OA with hands-on activities.

Arctic

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 collaborated with the Alaska Ocean Acidification Network and the Ocean Acidification Research Center (University of Alaska, Fairbanks) to include two Beaufort Sea moorings with pCO_2, oxygen, and temperature sensors. BOEM has an additional mooring near the Boulder Patch Area of Special Biological Concern in the Beaufort Sea. This sensor detects seawater pH variation in relation to freshwater run-off. Data from these Arctic moorings facilitates 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. NSF provided ongoing funding for the Beaufort Sea Lagoons LTER site. This LTER supports the collection of long-term data on primary productivity, nutrient cycling, the carbonate system, and other data relevant to OA research.

Theme 3. Improving Models of the Effects of Ocean Acidification on Ecosystems and Society
In FY 2018, NOAA supported 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.

Theme 4. Technology Development and Standardization of Methods
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, including several sea trials in the Gulf of Alaska and in the Chukchi Sea. This study facilitates a better understanding of oceanic uptake of CO_2 in the Arctic and potential effects related to offshore oil and gas activities.

Antarctic

Theme 1. Research to Understand Responses to Ocean Acidification
SI's Marine Global Earth Observatory, Antarctic Peninsula (64-69°S), funded by NSF, measured carbonate and non-carbonate chemistry parameters to investigate the correlation of pH variability with benthic and water column biological productivity.

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.

Appendix A

Table 1. Summary of all agency-funded ocean acidification research and monitoring activities

Theme	FY 2018 Budget ($K)	FY 2019 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification	5,677	7,568	Contributing
	11,867	9,104	Primary
	17,544	16,672	Total
2. Monitoring of ocean chemistry and biological impacts	27,796	60,405	Contributing
	6,237	6,920	Primary
	34,034	67,325	Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms	2,011	2,341	Contributing
	2,064	2,752	Primary
	4,075	5,093	Total
4. Technology development and standardization of measurements	597	2,315	Contributing
	2,005	721	Primary
	2,602	3,036	Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems	266	318	Contributing
	655	638	Primary
	921	956	Total
6. Education, outreach, and engagement on ocean acidification	785	149	Contributing
	3,477	3,368	Primary
	4,262	3,517	Total
7. Data management and integration	1,893	2,669	Contributing
	1,321	1,839	Primary
	3,214	4,508	Total
8. Other ocean acidification research and monitoring activities	632	100	Contributing

	1,991	1,921	Primary
	2,623	2,021	Total
Total	39,658	75,866	Total Contributing
	29,616	27,263	Total Primary
	69,274	103,128	Grand Total

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

Theme	FY 2018 Budget ($K)	FY 2019 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification			Contributing
		149	Primary
		149	Total
2. Monitoring of ocean chemistry and biological impacts			Contributing
	349		Primary
	349		Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms			Contributing
			Primary
			Total
4. Technology development and standardization of measurements			Contributing
			Primary
			Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems			Contributing
			Primary
			Total
6. Education, outreach, and engagement on ocean acidification			Contributing
			Primary
			Total
7. Data management and integration			Contributing
			Primary
			Total
8. Other ocean acidification research and monitoring activities			Contributing

			Primary
			Total
Total			Total Contributing
	349	149	Total Primary
	349	149	Grand Total

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

Theme	FY 2018 Budget ($K)	FY 2019 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification			Contributing
			Primary
			Total
2. Monitoring of ocean chemistry and biological impacts			Contributing
	949	723	Primary
	949	723	Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms			Contributing
			Primary
			Total
4. Technology development and standardization of measurements			Contributing
			Primary
			Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems			Contributing
			Primary
			Total
6. Education, outreach, and engagement on ocean acidification			Contributing
	52	87	Primary
	52	87	Total
7. Data management and integration			Contributing
			Primary
			Total
8. Other ocean acidification research and monitoring activities			Contributing
			Primary

			Total
Total			Total Contributing
	1,001	810	Total Primary
	1,001	810	Grand Total

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

Theme	FY 2018 Budget ($K)	FY 2019 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification			Contributing
	275	301	Primary
	275	301	Total
2. Monitoring of ocean chemistry and biological impacts			Contributing
	158	132	Primary
	158	132	Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms	228	228	Contributing
			Primary
	228	228	Total
4. Technology development and standardization of measurements			Contributing
			Primary
			Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems			Contributing
			Primary
			Total
6. Education, outreach, and engagement on ocean acidification			Contributing
	99	1	Primary
	99	1	Total
7. Data management and integration			Contributing
		50	Primary
		50	Total
8. Other ocean acidification research and monitoring activities			Contributing
			Primary
			Total
Total	228	228	Total Contributing
	532	484	Total Primary
	760	712	Grand Total

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

Theme	FY 2018 Budget ($K)	FY 2019 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification			Contributing
			Primary
			Total
2. Monitoring of ocean chemistry and biological impacts			Contributing
			Primary
			Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms			Contributing
			Primary
			Total
4. Technology development and standardization of measurements			Contributing
			Primary
			Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems			Contributing
			Primary
			Total
6. Education, outreach, and engagement on ocean acidification			Contributing
	839	252	Primary
	839	252	Total
7. Data management and integration			Contributing
			Primary
			Total
8. Other ocean acidification research and monitoring activities			Contributing
			Primary
			Total
Total			Total Contributing
	839	252	Total Primary
	839	252	Grand Total

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

Theme	FY 2018 Budget ($K)	FY 2019 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification	250	250	Contributing
	250	250	Primary
	500	500	Total
2. Monitoring of ocean chemistry and biological impacts			Contributing
			Primary
			Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms	250	250	Contributing
	250	250	Primary
	500	500	Total
4. Technology development and standardization of measurements	100		Contributing
	100		Primary
	200		Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems			Contributing
			Primary
			Total
6. Education, outreach, and engagement on ocean acidification			Contributing
			Primary
			Total
7. Data management and integration			Contributing
			Primary
			Total
8. Other ocean acidification research and monitoring activities	100	100	Contributing
	100	100	Primary
	200	200	Total
Total	700	600	Total Contributing
	700	600	Total Primary
	1,400	1,200	Grand Total

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

Theme	FY 2018 Budget ($K)	FY 2019 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification	4,232	4,717	Contributing
	4,280	4,518	Primary
	8,512	9,235	Total
2. Monitoring of ocean chemistry and biological impacts	1,595	2,488	Contributing
	3,397	4,516	Primary
	4,993	7,004	Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms	1,331	1,625	Contributing
	1,625	2,290	Primary
	2,956	3,915	Total
4. Technology development and standardization of measurements	472	2,293	Contributing
	612	545	Primary
	1,084	2,838	Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems	64	80	Contributing
	655	638	Primary
	719	718	Total
6. Education, outreach, and engagement on ocean acidification	735	99	Contributing
	996	1,268	Primary
	1,731	1,367	Total
7. Data management and integration	445	597	Contributing
	1,321	1,789	Primary
	1,766	2,386	Total
8. Other ocean acidification research and monitoring activities	35		Contributing
	1,891	1,821	Primary
	1,926	1,821	Total
Total	8,910	11,900	Total Contributing
	14,776	17,385	Total Primary
	23,686	29,284	Grand Total

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

Theme	FY 2018 Budget ($K)	FY 2019 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification	20	20	Contributing
	10	10	Primary
	30	30	Total
2. Monitoring of ocean chemistry and biological impacts	84	54	Contributing
	212	279	Primary
	296	333	Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms			Contributing
			Primary
			Total
4. Technology development and standardization of measurements			Contributing
			Primary
			Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems			Contributing
			Primary
			Total
6. Education, outreach, and engagement on ocean acidification			Contributing
	22	8	Primary
	22	8	Total
7. Data management and integration			Contributing
			Primary
			Total
8. Other ocean acidification research and monitoring activities			Contributing
			Primary
			Total
Total	104	74	Total Contributing
	244	297	Total Primary
	348	371	Grand Total

Table 9. Summary of NSF-funded ocean acidification research and monitoring activities

Theme	FY 2018 Budget ($K)	FY 2019 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification	307	1,323	Contributing
	6,932	3,791	Primary
	7,239	5,114	Total
2. Monitoring of ocean chemistry and biological impacts	25,723	57,326	Contributing
	1,067	1270	Primary
	26,790	58,596	Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms			Contributing
	189	190	Primary
	189	190	Total
4. Technology development and standardization of measurements			Contributing
	1,283	166	Primary
	1,283	166	Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems			Contributing
			Primary
			Total
6. Education, outreach, and engagement on ocean acidification			Contributing
	1,469	1,752	Primary
	1,469	1,752	Total
7. Data management and integration	1,448	2,072	Contributing
			Primary
	1,448	2,072	Total
8. Other ocean acidification research and monitoring activities	497		Contributing
			Primary
	497		Total
Total	27,975	60,721	Total Contributing
	10,940	7,169	Total Primary
	38,915	67,890	Grand Total

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

Theme	FY 2018 Budget ($K)	FY 2019 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification			Contributing
	15	85	Primary
	15	85	Total
2. Monitoring of ocean chemistry and biological impacts			Contributing
			Primary
			Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms			Contributing
		22	Primary
		22	Total
4. Technology development and standardization of measurements			Contributing
	10	10	Primary
	10	10	Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems			Contributing
			Primary
			Total
6. Education, outreach, and engagement on ocean acidification			Contributing
			Primary
			Total
7. Data management and integration			Contributing
			Primary
			Total
8. Other ocean acidification research and monitoring activities			Contributing
			Primary
			Total
Total			Total Contributing
	25	117	Total Primary
	25	117	Grand Total

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

Theme	FY 2018 Budget ($K)	FY 2019 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification	868	1258	Contributing
	105		Primary
	973	1258	Total
2. Monitoring of ocean chemistry and biological impacts	394	537	Contributing
	105		Primary
	499	537	Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms	202	238	Contributing
			Primary
	202	238	Total
4. Technology development and standardization of measurements	25	22	Contributing
			Primary
	25	22	Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems	202	238	Contributing
			Primary
	202	238	Total
6. Education, outreach, and engagement on ocean acidification	50	50	Contributing
			Primary
	50	50	Total
7. Data management and integration			Contributing
			Primary
			Total
8. Other ocean acidification research and monitoring activities			Contributing

			Primary
			Total
Total	1,741	2,343	Total Contributing
	210		Total Primary
	1,951	2,343	Grand Total