SEVENTH REPORT ON FEDERALLY FUNDED OCEAN ACIDIFICATION RESEARCH AND MONITORING ACTIVITIES

A Report by the

INTERAGENCY WORKING GROUP ON OCEAN ACIDIFICATION

SUBCOMMITTEE ON OCEAN AND SCIENCE TECHNOLOGY

COMMITTEE ON ENVIRONMENT

of the

NATIONAL SCIENCE & TECHNOLOGY COUNCIL

September 2023

About the National Science and Technology Council

The National Science and Technology Council (NSTC) is the principal means by which the Executive Branch coordinates science and technology policy across the diverse entities that make up the federal research and development enterprise. A primary objective of the NSTC is to ensure science and technology policy decisions and programs are consistent with the President's stated goals. The NSTC prepares research and development strategies that are coordinated across federal agencies aimed at accomplishing multiple national goals. The work of the NSTC is organized under committees that oversee subcommittees and working groups focused on different aspects of science and technology. More information is available at http://www.whitehouse.gov/ostp/nstc.

About the Office of Science and Technology Policy

The Office of Science and Technology Policy (OSTP) was established by the National Science and Technology Policy, Organization, and Priorities Act of 1976 to provide the President and others within the Executive Office of the President with advice on the scientific, engineering, and technological aspects of the economy, national security, homeland security, health, foreign relations, the environment, and the technological recovery and use of resources, among other topics. OSTP leads interagency science and technology policy coordination efforts, assists the Office of Management and Budget with an annual review and analysis of federal research and development in budgets, and serves as a source of scientific and technological analysis and judgment for the President with respect to major policies, plans, and programs of the federal Government. More information is available at http://www.whitehouse.gov/ostp.

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 (P.L. 111-11, Subtitle D).

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 to produce a biennial report to Congress on federal ocean acidification activities. The previous biennial reports can be found on the IWG-OA's website.

Copyright Information

NATIONAL SCIENCE & TECHNOLOGY COUNCIL

Chair

Arati Prabhakar, Director, Office of Science and Technology Policy

(Acting) Executive Director

Kei Koizumi, Principal Deputy Director for Policy, Office of Science and Technology Policy

COMMITTEE ON ENVIRONMENT

Co-Chairs

Jane Lubchenco, Deputy Director for Climate and Environment, Office of Science and Technology Policy

Rick Spinrad, Under Secretary of Commerce for Oceans and Atmosphere, National Oceanic and Atmospheric Administration, Department of Commerce

Chris Frey, Deputy Assistant Administrator for Science Policy, Office of Research and Development, Environmental Protection Agency

SUBCOMMITTEE ON OCEAN SCIENCE AND TECHNOLOGY

Co-Chairs

Alexandra Isern, National Science Foundation

Danielle Farelli, Office of Science and Technology Policy

Steve Thur, National Oceanic and Atmospheric Administration

Tom Drake, Office of Naval Research, Department of Defense

Staff

Stacy Aguilera-Peterson, Chief Executive Secretary, National Science Foundation

Amelia-Juliette Demery, Executive Secretary, National Science Foundation

Victoria Moreno, Executive Secretary, National Oceanic and Atmospheric Administration

INTERAGENCY WORKING GROUP ON OCEAN ACIDIFICATION

Chair

Dwight Gledhill, National Oceanic and Atmospheric Administration

Staff

Courtney Witkowski, National Oceanic and Atmospheric Administration

Members

Krisa Arzayus, National Oceanic and Atmospheric Administration

Christina Bonsell, Bureau of Ocean Energy Management

Cheryl Brown, Environmental Protection Agency

Jennifer Bucatari, Bureau of Ocean Energy Management

Shallin Busch, National Oceanic and Atmospheric Administration

Meaghan Cuddy, Department of State

Eva DiDonato, National Park Service

Regina Easley, National Institute of Standards and Technology

Henrietta Edmonds, National Science Foundation

Wayne Estabrooks, United States Navy

Richard Feely, National Oceanic and Atmospheric Administration

Holly Galavotti, Environmental Protection Agency

Patrick Hogan, National Oceanic and Atmospheric Administration

Alyse Larkin, National Oceanic and Atmospheric Administration

Pete Leary, Fish and Wildlife Service

Laura Lorenzoni, National Aeronautics and Space Administration

Whitman Miller, Smithsonian Institution

Rachael Novak, Bureau of Indian Affairs

Caird Rexroad, Department of Agriculture

Tim Sullivan, Department of Agriculture

Jason Waters, National Institute of Standards and Technology

Kim Yates, United States Geological Survey

Table of Contents

List of Acronyms

AOOS	Alaska Ocean Observing System
BIA	Bureau of Indian Affairs
BOEM	Bureau of Ocean Energy Management
CMIP6	Coupled Model Intercomparison Project Phase 6
CO_2	carbon dioxide
CTD	conductivity, temperature, and depth instrument
DIC	dissolved inorganic carbon
DFO	Department of Fisheries and Oceans, Canada
DOS	United States Department of State
eDNA	environmental deoxyribonucleic acid
EPA	Environmental Protection Agency
EXPORTS	EXport Processes in the Ocean from Remote Sensing
FOARAM	Federal Ocean Acidification Research and Monitoring Act of 2009
FWS	United States Fish and Wildlife Service
FY	Fiscal Year
GLIMR	Geosynchronous Littoral Imaging and Monitoring Radiometer
GO-BGC	Global Ocean Biogeochemistry
GO-SHIP	Global Ocean Ship-based Hydrographic Investigation Program
GOA-ON	Global Ocean Acidification Observing Network
IOOS	United States Integrated Ocean Observing System
IPCC	Intergovernmental Panel on Climate Change
IWG-OA	Interagency Working Group on Ocean Acidification
LNE	Laboratoire national de métrologie et d'essaiso
LTER	Long-Term Ecological Research
M	million
MACAN	Mid-Atlantic Ocean Acidification Network
NANOOS	Northwest Association of Networked Ocean Observing Systems
NASA	National Aeronautics and Space Administration
NCEI	National Centers for Environmental Information
NERR	National Estuarine Research Reserve
NEP	EPA's National Estuary Programs
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
NSF	National Science Foundation
NSTC	National Science and Technology Council
OA	ocean acidification
OADS	Ocean Acidification Data Stewardship
OASeS	Ocean Acidification Sentinel Site
OCADS	Ocean CArbon Data System
OOI	Ocean Observatories Initiative
OSTP	Office of Science and Technology Policy
PACE	Plankton, Aerosol, Cloud, and ocean Ecosystem
pCO_2	partial pressure of carbon dioxide
ppm	parts per million
RM's	reference materials
SBG	Surface Biology and Geology
TA	total alkalinity

UNOLS	University-National Oceanographic Laboratory System
USDA	United States Department of Agriculture
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. The Biden-Harris Administration has made it a priority to advance ocean acidification research and monitoring.

This document summarizes federal activities on OA in Fiscal Years (FY) 2020 and 2021. It is organized into sections corresponding to the nine geographic regions in which federal agencies studied OA in FY 2020 and FY 2021, 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 agency.[1] 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 summarizes expenditure amounts for individual agencies' OA research and monitoring activities. Expenditures are classified as having a primary focus on OA or contributing to activities that, while designed for other purposes, provide information useful for understanding OA. In FY 2020, federal agencies provided approximately $23.7 million (M) toward activities with a primary focus on OA and an additional $28.9 M for contributing activities. In FY 2021, federal funding was approximately $30.2 M for primary activities and $32.6 M for contributing activities. This investment has created and provided continued support for jobs in the science, engineering, and technology sectors and has contributed towards building the resilience of coastal communities and related economies to the many threats from OA. In FY 2020 and FY 2021, the COVID-19 pandemic caused a large amount of research and monitoring to be delayed due to lab closures or other restrictions on in-person work.

The investments made by federal agencies will further our understanding of ocean and coastal acidification, including its impacts to species, ecosystems, coastal communities, and industries. This report communicates the advancements made by the FY 2020 and FY 2021 investments in observing and modeling acidification, understanding biological impacts, and determining potential societal impacts and adaptation strategies.

Work funded by agencies addressed key gaps in both monitoring and modeling of OA, allowing for better understanding of current and future acidification dynamics.

- *Coastal acidification monitoring and modeling*: New investments were made in coastal acidification monitoring and in research on processes, such as land-based inputs that contribute to the variability in the coastal zone. Regional models were also developed to capture drivers of coastal acidification. It is a priority to better understand acidification in estuaries and other coastal areas, as many important yet vulnerable species are found in these habitats.
- *Biological monitoring*: Agencies increased co-located chemical OA and biological monitoring, including eDNA sampling, and also funded research to identify potential bioindicators (i.e., species sensitive to OA to be routinely monitored). These efforts are key to understanding how changes in ocean chemistry affect marine species.

[1] Interagency Working Group on Ocean Acidification of the National Science and Technology Council (2014). Strategic Plan for Federal Research and Monitoring of Ocean Acidification. Executive Office of the President of the United States, p.p. 86. https://oceanacidification.noaa.gov/wp-content/uploads/2023/06/IWGOA-Strategic-Plan.pdf

- *Observation optimization studies*: These new research projects will identify how observation networks can be better designed for stakeholder needs and utilize technology such as autonomous vehicles.

Another key area of focus is understanding the impacts of OA to species, habitats, and ecosystems; agencies made advancements in both research on impacts to species and biological modeling.

- *Multi-stressor research:* Understanding the impacts of OA in conjunction with other stressors such as warming, hypoxia, and nutrient importance is a key priority for biological research. Agencies funded many multi-stressor studies, including ones on corals, Dungeness crab, Arctic cod, and the Pacific oyster, among others.
- *Seagrass and kelp OA mitigation*: Many stakeholders are interested in understanding how aquatic vegetation such as seagrass and kelp can mitigate OA at local scales; new research will provide more information on the viability of this technique.
- *Population and ecosystem impacts*: New research is focused on understanding impacts to whole populations and ecosystems, rather than just the sensitivity of individuals. This includes multigenerational studies, which look at the potential for a population to adapt over generations, and studies on impacts to the base of food webs.
- *Modeling impacts to economically important species*: Agencies funded models that considered OA impacts to economically valuable species, including oysters, Dungeness crab, and Pacific cod.

Significant investments were also made to understand the potential impacts of OA to coastal communities, conduct outreach and education with those communities, and research potential adaptation measures that can be enacted.

- *Regional vulnerability assessments*: New projects were funded to work with communities or industries to understand their vulnerability to OA and to identify potential adaptation strategies. Projects are working with a variety of topics, including oyster aquaculture and restoration in the Mid-Atlantic, the Atlantic sea scallop fishery, the shellfish industry on the West Coast, and traditional and emerging coastal industries in Alaska.
- *Educational materials*: Agencies supported new curriculum development and workshops for students of various ages.

In addition to these three broad areas, agencies continued investing in technology development and data management, which are both integral to supporting monitoring and research. Agencies invested in both new sensors for measuring carbonate chemistry and new technologies, including autonomous vehicles that can expand our ability to monitor at greater spatial scale and in the subsurface. Additionally, continued national investment in data management will allow for ocean carbon and OA data to be discovered and accessed by a diverse set of users.

Global

Ocean acidification is a global phenomenon; however, few research projects are truly global. 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" despite the entire portfolio building 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, leveraging federal and private satellites with ocean observing capabilities. NASA funded efforts to

reduce uncertainty when measuring phytoplankton chlorophyll and other ocean biology, ecology, and biogeochemistry data products retrieved from Earth observing satellites.

NASA continued to support the implementation of the Plankton, Aerosol, Cloud, and ocean Ecosystem (PACE) satellite mission (launching in 2024), and formulation of the Surface Biology and Geology (SBG) satellite mission (launching no earlier than 2028) and Geosynchronous Littoral Imaging and Monitoring Radiometer (GLIMR) instrument (expected to be completed by 2024). These Earth observing investments, once in orbit, will advance the understanding of ocean biogeochemical cycling and aid in quantifying changes in ecosystem function due to natural and anthropogenic forcing from environmental variability and climate change. PACE, SBG, and GLIMR will extend key Earth system data records on global ocean ecology and biogeochemistry and inform carbon monitoring and management efforts.

NASA supported interdisciplinary research to investigate the processes contributing to the variability of OA and of the air-sea carbon dioxide flux in the ocean basins of the Southern Hemisphere, with a focus on how these factors impact biological productivity. This work included the development of models to examine how the linkages between atmospheric carbon, oceanic carbon, OA, and biological productivity differ along north/south and onshore/offshore gradients, including how they relate to the interannual variability in sea ice presence and concentration.

NOAA worked with Fisheries and Oceans Canada (DFO) under their OA Collaboration Framework to advance joint activities related to OA monitoring, research, experimentation, and modeling on species response to OA. In FY 2020, the NOAA-DFO collaboration funded six collaborative projects with NOAA OA Program and DFO funding support. The projects' topics range from assessing OA impact in fish larvae and Dungeness crab, to an inter-model comparison of carbonate system variables, to enhancing analytical knowledge transfer.

NSF supported several awards focused on the effects of OA, and the interplay of OA and temperature stressors, on corals, including two projects aimed at understanding the mechanisms of coral skeletal growth. One experimental study focused on the effects of pH on mussels and their foundational ecological role, while another project examined the effects of climate change variables including OA on carbon transfer by and between phytoplankton and heterotrophic bacteria.

NSF funded two projects aimed at reconstruction of past pH from proxy records. One project aimed to synthesize and re-evaluate coral-based records, utilizing a new understanding of coral calcification. The other was a laboratory calibration of the boron isotope proxy in shells of planktonic foraminifera, single-celled organisms found in the surface ocean. Boron isotope proxy is a powerful tool for understanding past surface seawater acidity levels.

Theme 2. Monitoring of Ocean Chemistry and Biological Impacts

NOAA and NSF continued to support global hydrographic surveys as part of the international Global Ocean Ship-based Hydrographic Investigation Program (GO-SHIP). Each agency supports carbon measurements on two to three cross-ocean basin, full-water column cruises each year. This program provides high-quality, high-spatial, and vertical resolution measurements of a suite of physical, chemical, and biological parameters, including dissolved inorganic carbon (DIC), total alkalinity (TA), and pH throughout the full water column in open-ocean waters. The program provides global measurements of the highest required accuracy, with approximately decadal resolution of the changes in inventories of heat, freshwater, carbon, oxygen, nutrients, and transient tracers. Surface CO_2 measurements from this program, moorings, and ships of opportunity are collated in the Surface Ocean CO_2 Atlas. The 2021 version of the Atlas contained 30.6 million observations of surface ocean partial pressure CO_2 collected between 1957 and 2021. These data 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.

NOAA maintains 23 OA buoys globally, some of which include collaboration and co-funding with international partners, which have the sensor suite for maintaining an OA time-series. OA international buoy locations include the 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's primary investment has been within U.S. national waters most relevant to NOAA-managed resources, including oceanic waters housing major fisheries (e.g., Gulf of Alaska, Gulf of Maine, California Current), along coastal systems (e.g., coastal Louisiana, Puget Sound), and U.S. coral reef ecosystems (e.g., Puerto Rico, Florida, Hawai'i, Grey's Reef). NOAA maintains an additional 12 open-ocean moorings that collect CO_2 data from surface seawater and marine boundary air to evaluate the variability in CO_2 uptake from the atmosphere to the ocean.

NOAA continued to operate the largest ship-of-opportunity effort for surface CO_2 observations in the world, collecting underway pCO_2 data from 17 commercial and research vessels in coastal and international waters to constrain the flux of CO_2 across the air-water interface. NOAA also executes quadrennial surveys of OA and marine species throughout U.S. coastal marine waters in the Gulf of Alaska, along the West Coast, throughout the U.S. Pacific Islands, and throughout the Gulf of Mexico, the Mid-Atlantic, and New England.

NSF also supports mid-ocean time series stations in both the Atlantic and Pacific Oceans, the Bermuda Atlantic Time-series Study and Hawai'i Ocean Time-series. Observations at these sites included measurements of ocean primary productivity and changes in the ocean biota, nutrients, pH, and carbonate chemistry. The University-National Oceanographic Laboratory System (UNOLS) vessels provided significant ship support for sampling at these stations and for numerous other projects. The NSF Ocean Observatories Initiative (OOI) 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 supported international carbon cycling planning and coordinating activities through the Scientific Committee on Oceanic Research.

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

NASA supported modeling studies through its Global Modeling and Assimilation Office to conduct observation system simulation experiments and to generate seasonal forecasts to examine the fate of carbon in the ocean and its impacts on aquatic ecosystems. This investment was a component of NASA's EXport Processes in the Ocean from Remote Sensing (EXPORTS) project, a larger multi-year effort consisting of two field campaigns aimed at developing a predictive understanding of the export and fate of global ocean net primary production and its implications for the Earth's carbon cycle in present and future climates.

NOAA's Earth system modeling 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 with a simple biogeochemistry and 1/4-degree global resolution with a comprehensive biogeochemistry and ecosystem from the fully coupled chemistry-carbon-climate

Earth System Model ESM4.1. These results were incorporated into publications on twenty-first century ocean warming, acidification, deoxygenation, and upper ocean nutrient decline from Coupled Model Intercomparison Project Phase 6 (CMIP6) model projections and the 6th Intergovernmental Panel on Climate Change (IPCC) Assessment report. 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 continued 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

In FY 2021, NSF committed five years of funding to a Mid-Scale Research Infrastructure project called the Global Ocean Biogeochemistry (GO-BGC) Array. GO-BGC will deploy 500 profiling floats equipped with pH, oxygen, nitrate, CTD, and optical sensors to contribute to the international biogeochemical Argo program. NOAA worked to develop, calibrate, and demonstrate the efficacy of BGC-Argo profiling floats equipped with temperature, salinity, and biogeochemical sensors for pH, oxygen, nitrate, and optical observations to observe biogeochemical properties in the upper 2,000 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. NOAA supported the redesign of the float bodies to include six sensors, more batteries, and improved oxygen and pH sensors.

NASA supported technology investments for building and deploying BGC-Argo profiling floats to provide sustained year-round circumpolar sampling of optical, carbonate, and other parameters relevant to OA in the Southern Ocean. This investment enables the sustained presence of BGC-Argo profiling floats for monitoring phytoplankton, particle, and carbon dynamics via bio-optical measurements in three-dimensional space and time for a historically under-sampled and under-monitored region.

NIST worked to develop capabilities to provide traceable measurements for the carbon dioxide system in seawater and to support global efforts to create a robust production model for seawater CO_2 reference materials. NIST worked with Laboratoire national de métrologie et d'essaiso (LNE) and others to establish the Seawater pH Task Group within the Consultative Committee for Metrology in Chemistry and Biology (CCQM) at the International Bureau of Weights and Measures. NIST and LNE coordinated a pilot interlaboratory study (CCQM-P221) on determining hydrogen ion activity and total pH in artificial seawater buffer with five national metrology laboratories submitting measurement results. Laboratory based experiments were conducted to refine the definition of pH in ionic media, such as seawater. This work will aid in establishing uncertainties in seawater pH.

A subcommittee within the IWG-OA that included NIST, NSF, NOAA, and EPA began meeting to coordinate a transition plan for the NSF-supported Scripps Institution of Oceanography carbon dioxide reference material (RM) program, the sole source of ocean carbon RMs, whereby NIST will eventually provide certified values for TA and total DIC. NIST worked to assess existing measurement capabilities and outline additional instrumentation, facilities, and staff required to provide these values. At the international level, NIST participated in a meeting organized by the International Ocean Carbon Coordination Project (IOCCP) to create a global multi-distribution center model for ocean carbon RMs.

NOAA worked with Saildrone, Inc. to field test the capacity of this wind- and solar-powered autonomous surface vehicle for CO_2 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 DIC using spectrophotometry and infrared sensors, a commercial TA 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.

In FY 2021, NSF renewed support to produce CO_2 reference standards for DIC and TA (see above). NSF funded a new project to improve accuracy and uncertainty associated with pCO_2 calculations from autonomous pH sensors. Three new projects focused on improved understanding of the physical chemistry of the carbonic acid system and the solubility of calcium carbonate mineral phases over a range of conditions, including seawater solutions with non-standard major ion concentrations.

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 IPCC activities related to the Sixth Assessment Cycle. The EPA conducted a 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, postponed to later occur in 2022.

NOAA continued to foster the activities and growth of the Global Ocean Acidification Observing Network (GOA-ON), with the NOAA Ocean Acidification Program (OA Program) Director serving on the executive council and NOAA OA Program fellow serving as one of the Executive Secretaries. NOAA also funded the GOA-ON data portal, hosted by the Northwest Association of Networked Ocean Observing Systems (NANOOS), and funded the participation of the NANOOS director as one of the GOA-ON chairs. In previous fiscal years, NOAA has worked with GOA-ON and other international partners to provide in-person training and outreach. Due to the COVID-19 pandemic, outreach in 2020 and 2021 was virtual. The NOAA OA Program fellows led the development of OA Week, an online webinar series for the international community. The 2020 event was two days and hosted 48 webinars in 10 sessions. The 2021 event grew to a week-long event with over 50 webinars and interactive panels. All 2021 sessions were recorded and are publicly available online. In FY 2021, the NOAA OA Program helped to launch the GOA-ON UN Decade Programme— Ocean Acidification Research for Sustainability (OARS) — producing an introductory video and infographics to use as communication tools. At the end of FY 2021, GOA-ON had over 1,000 members representing 105 nations and territories. The Pier2Peer Program, a GOA-ON mentorship program run by the NOAA OA Program, had over 100 active mentor-mentee pairs.

Theme 7. Data Management, Integration, and Synthesis

In FY 2020 and FY 2021, the Ocean Acidification Data Stewardship (OADS) project at NOAA National Centers for Environmental Information (NCEI) provided dedicated long-term archival, online data discovery, and access for a diverse range of OA-related data sets, including chemical, physical, and biological OA observations, as well as those from multi-disciplinary field observations, laboratory experiments, model outputs, and socioeconomic studies. OADS featured a community-driven rich metadata template and was committed to provide the best data management support for OA research. OADS served NOAA OA Program-funded data producers only. NOAA also supported the

Scientific Data Integration System (SDIS) development, which provides a single-entry point for all carbon data submitted to NCEI, including data for synthesis products.

The Ocean Carbon Data System (OCADS) was another data management entity at the NOAA National Centers for Environmental Information, which houses chemical oceanographic observations, especially ocean carbon data, collected from research vessels, ships of opportunity, moorings, and other uncrewed platforms. OCADS used the same data management infrastructure as OADS. It serves ocean carbon data producers from around the world.[2]

NOAA supported the Carbon Data Management and Synthesis Project that prioritizes workup and analysis of data obtained through efforts funded by the Global Ocean Monitoring and Observing Program (GOMO), including the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP), the partial pressure of CO_2 (pCO_2) on ships of opportunity effort (SOOP-CO2), and the pCO_2 on moorings effort. Data from other investigators worldwide is also incorporated. Synthesis efforts addressed where anthropogenic carbon enters the ocean, where it is stored, how patterns of uptake and storage are changing, and how carbon uptake impacts marine inorganic carbon chemistry.

National

Like global-scale OA projects, relatively few OA research projects are truly national. 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 broader 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 USDA National Institute of Food and Agriculture provided research support over the FY 2020-2021 period for projects focused on monitoring, research, and modelling. These include projects on both the U.S. East and West coasts and range from the use of remote sensing to evaluate environmental condition and quality, understanding the stress physiology of coastal aquatic organisms (especially those that form the basis of coastal aquaculture), and the development of novel tools and management strategies for mitigating climate impacts on food production in coastal areas.

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.

[2] The Ocean Acidification Data Stewardship project and the Ocean Carbon Data System were replaced with the newly merged Ocean Carbon and Acidification Data System in 2022, where users can now access data.

Theme 2. Monitoring of Ocean Chemistry and Biological Impacts

Eleven of the EPA's National Estuary Programs (NEPs) monitored *in situ* coastal acidification using autonomous pH and pCO_2 sensors or began development of such monitoring programs.[3] This monitoring is capturing the high-resolution data necessary to understand these estuaries' vulnerability 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 EPA published a report, *Measuring Coastal Acidification Using In Situ Sensors in the National Estuary Program*, which examines challenges, lessons learned, and solutions regarding autonomous acidification monitoring sensors in estuarine environments.[4] EPA and its partners also published a paper, *Integrating High-Resolution Coastal Acidification Monitoring Data Across Seven United States Estuaries*, which compared daily to seasonal variability in carbonate chemistry and described regional differences in drivers.[5] In addition, EPA evaluated the quality assurance and quality control measures employed across the country by the NEPs to share the state of the science and best practices in coastal acidification monitoring.

The EPA initiated the incorporation of a coastal acidification pilot indicator into the 2020 National Coastal Condition Assessment Survey. During FY's 2020-2021, TA was measured at 899 National Coastal Condition Assessment estuarine sites and will be used to establish a baseline and assess patterns in buffering against coastal acidification and model TA in estuaries.

The EPA initiated a national analysis of the status and trends in U.S. coastal stream CO_2 chemistry, encompassing more than 170 sites along the West, Gulf of Mexico, and East coasts. Results of the analysis will characterize regional patterns and long-term trends in land-based acidification pressures in U.S. estuaries and characterize the relative vulnerabilities of U.S. estuaries to further acidification from land-based and atmospheric CO_2 sources.

NOAA grew the National OA 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 four-year cycle and occurred along the U.S. West Coast and the Gulf of Mexico in 2021. NOAA supported long-term monitoring of biological, physical, and socioeconomic indicators throughout the U.S. Pacific Islands, Atlantic, Gulf of Mexico, and Caribbean coral reef areas as a part of the National Coral Reef Monitoring Program (NCRMP).

USGS continued operating its Carbon Analytical Laboratory and supported carbonate system measurements coordinated with coral reef studies in the Florida Keys and Pacific Islands, sediment analyses in the Gulf of Mexico, and autonomous carbon system analyses in Tampa Bay, Florida.

[3] National Estuary Program sites engaged in coastal acidification monitoring include 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.

[4] U.S. Environmental Protection Agency. 2021. Measuring Coastal Acidification Using In Situ Sensors in the National Estuary Program. Washington D.C., Document No. EPA-842-R-21001.

[5] Rosenau, N. A., Galavotti, H., Yates, K. K., Bohlen, C. C., Hunt, C. W., Liebman, M., Brown, C. A., Pacella, S. R., Largier, J. L., Nielsen, K. J., Hu, X., McCutcheon, M. R., Vasslides, J. M., Poach, M., Ford, T., Johnston, K., & Steele, A. (2021). Integrating high-resolution coastal acidification monitoring data across seven united states estuaries. Frontiers in Marine Science, 8, 1066.

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

NOAA scientists started a project to use an Earth System Model to study trends, variability, and extremes in U.S. waters for four key ecosystem stressors: OA, warming, deoxygenation, and nutrient availability.

USGS continued to support 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 continued to support use of its *Guidelines for Measuring Changes in Seawater pH and Associated Carbonate Chemistry in Coastal Environments of the Eastern United States*.[6] These guidelines target various audiences with differing areas of expertise, from shellfish growers to citizen monitoring groups and advanced chemistry laboratories.

NOAA scientists continued to develop new sensors that measure DIC and pCO_2 together, and sensors that measure TA at testbeds to improve the NOAA Ocean Acidification Observation Network.

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 worked to quantify the potential influence of OA on ecosystem services and complete an assessment of the economic impacts of OA and climate change on shellfisheries in coastal waters of the U.S. Exclusive Economic Zone.

The U.S. Coral Reef Task Force was established in 1998 by executive order to lead U.S. efforts to preserve and protect coral reef ecosystems, and a number of federal agencies are members. A component of NASA's investment in the task force supported the study of OA and aragonite saturation on corals and their reef ecosystems.

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

The EPA continued to update its website for ocean and coastal acidification, including information on the 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.

The IWG-OA continued to support the OA Information Exchange, a collaborative online community of practice. This meets the requirement in the FOARAM Act of 2009 for the IWG-OA to make OA information accessible via electronic means. The website serves all stakeholders interested in OA and allows users to share resources and events, ask questions, and network with others across disciplines

[6] Pimenta, A. R., & Grear, J. S. (2018). Guidelines for Measuring Changes in Seawater pH and Associated Carbonate Chemistry in Coastal Environments of the Eastern United States.

and geographic regions. The Northeast Regional Association of Coastal Ocean Observing Systems operates the OA Information Exchange with funding from NOAA. By the end of FY 2021, the site had over 1,400 members, including many from the international community, and included robust contributions by the OA community.

NOAA staff engaged in various OA-related education, outreach, and engagement activities, in addition to multiple NOAA websites and social media accounts highlighting OA. NOAA trained many undergraduate and graduate students in OA research methodologies through various internship and fellowship programs. NOAA continued the Sharing OA Resources for Communicators and Educators webinar series.

NOAA continued the OA Education Mini Grant program. The awardees are working to develop OA curricula, educational multimedia tools, and citizen-science programs on the Mid-Atlantic, Gulf of Mexico, Alaska, and West Coasts of the United States. The NOAA Bay Watershed Education and Training program, which provides meaningful watershed educational experiences for students and related professional development for teachers, continued to fund projects that had OA components in FYs 2020-2021.

NOAA Sea Grant and state Sea Grant offices raised awareness about OA through education and extension efforts. In 2020, NOAA hosted a workshop on harmful algal blooms and OA to identify research needs and priorities across regions to understand interactions between these stressors better.

NSF and NASA provided support for the Ocean Carbon and Biogeochemistry Project Office, which supports research and activities pertaining to ocean acidification and carbon cycling with community engagement and outreach components.

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 an Ocean Acidification Information Exchange steering committee member.

Theme 7. Data Management, Integration, and Synthesis

The Biological and Chemical Oceanography Data Management Office handles data management for the NSF Biological and Chemical Oceanography Programs, as well as ongoing support for 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.

NOAA funded a data synthesis project to compile and synthesize over two decades of discrete carbonate, nutrient, and hydrographic data measurements from North America's continental shelves, produced as the coastal ocean data analysis product (CODAP).

The EPA evaluated the use of public data repositories and shared best practices for managing, storing, and sharing of ocean and coastal acidification monitoring data collected by the National Estuary Programs and citizen science groups.

Theme 8. Other research and monitoring activities

NOAA supports the NOAA OA Program 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.

In the Consolidated Appropriations Act of 2019 (Public Law 116-6 § 770), Congress directed USDA to form a working group to study how mangroves, kelp, and other vegetation could contribute to deacidification of the ocean; to study how farming of these species could counter acidification while also providing feedstock; and to conduct pilot-scale research on farming kelp and seagrass. In FY 2021, Congress provided USDA funding to support the Working Group's Efforts; these funds were directed to the Agricultural Research Service, who formed the Working Group and entered a partnership with the Bigelow Laboratory for Ocean Sciences to support the development of a report and funding pilot projects. The working group includes 46 members representing EPA, NSF, and various Agencies in the Departments of Commerce, Energy, Interior, Health and Human Services, Defense, and Agriculture.

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 continued its study of coastal acidification impacts on shellfish in Narragansett Bay, Rhode Island.

NOAA maintains shared-user experimental facilities to study species responses to OA at the Northeast Fisheries Science Center's Highlands, New Jersey, and Milford, Connecticut, laboratories. These labs conducted OA research on the Eastern oyster, Atlantic surfclam, Atlantic sea scallop, blue mussel, American horseshoe crab, summer flounder, winter flounder, and Atlantic silverside. In FY 2021, NOAA started a long-term, multigenerational study with sea scallops to understand their tolerance and adaptive potential. NOAA also started a project to use benthic habitat sampling to understand and identify conditions where surfclams are vulnerable to OA, which will provide useful information for modeling future impacts to the fishery. A new project with blue mussels examines how OA may enhance metal uptake, which has implications for aquaculture and seafood safety.

Rhode Island Sea Grant supported research on the impact of OA and other coastal stressors on oyster recruitment by funding the development of a larval rearing system, collection of broodstock and spawning of larvae from different locations, and research on the effects of stressors on oyster size and genetic diversity (University of Rhode Island). Woods Hole Sea Grant researched the effect of coastal acidification on shellfish through natural nutrient pollution gradients.

NOAA and DFO funded a joint project to develop laboratory protocols and understand infrastructure needs to maintain and culture Atlantic sea scallops.

NSF funded a project to reconstruct hydrographic conditions and pH in the Gulf of Maine, Nova Scotia Shelf, and Mid-Atlantic Bight over the past 250 years using geochemical proxies in annually banded clams and crustose coralline algae. NSF also funded a postdoctoral research fellowship investigating within-generational and multigenerational plasticity in response to co-occurring hypoxia and acidification in the forage fish Atlantic silverside.

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 DIC 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 information and improve understanding of the vulnerability of these coastal waters to coastal acidification.

Two papers focused on the scientific findings and the participatory science implications of the Shell Day project were published in 2021: *Community science for coastal acidification monitoring and research* and *Synoptic assessment of coastal total alkalinity through community science*. Shell Day was a multiagency and academic citizen science project that took place in 2018, supported by Northeast Coastal Acidification Network, the EPA, NOAA, and State agencies.

NASA supported research to examine the variability of the carbon cycle and OA within the Gulf of Maine, working to advance the understanding of processes that govern the variability of carbonate systems in coastal areas. These studies combine ecosystem monitoring, process studies, numerical modeling, and ocean color satellite data.

NOAA, Northeast Regional Association of Coastal Ocean Observing Systems, and the University of New Hampshire continued operating an OA mooring in the Gulf of Maine. NOAA maintained underway OA observing equipment on a commercial ship conducting regular transits between Boston, Massachusetts and Iceland and on a NOAA ship that conducts fisheries independent trawl surveys in Northeast waters. In FY 2020 and FY 2021, NOAA funded carbon chemistry sampling during four Northeast Fisheries Science Center's Ecological Monitoring cruises (six were planned but two were canceled due to COVID-19), and scientists also began collecting pteropods to research their potential as a bioindicator. NOAA funded two observing system optimization projects to design better the OA observing system for the Northeast and Mid-Atlantic regions. One project deployed autonomous underwater gliders with pH and other sensors and applied these data to an existing ocean ecosystem/biogeochemical model that resolves carbonate chemistry and its variability. The second project is developing a regionally downscaled projection for the Northeast, evaluating the ability of the existing observational network to detect changes in OA-relevant stressors for scallops, and proposing a process-based strategy for the observing network moving forward.

NOAA and DFO funded a project to enhance observations made along cruise lines of an ongoing Canadian monitoring program through an international collaborative effort to facilitate knowledge exchange. NOAA funded a project to acquire a prototype sensor capable of measuring both DIC and either pCO_2 or pH that will be used to monitor OA on the Northeast Fisheries Science Center's field surveys; the project work was not able to start due to COVID-19.

The Pioneer Array, an element of NSF's Ocean Observatories Initiative located between central New Jersey and Martha's Vineyard, Massachusetts, continued to provide considerable data to increase understanding of OA.

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

The EPA researched to predict responses of estuarine production and carbonate chemistry to nutrient loading using stable carbon isotopes.

NOAA funded a project expanding the Northeast Coastal Ocean Forecast System to develop OA detection and warning systems for coastal water quality and shellfish/aquaculture managers. An ongoing NOAA-funded data synthesis effort looked 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 U.S. 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 region's first three synoptic OA cruises. NOAA also funded Rutgers University to improve data assimilation algorithms to enable higher-resolution forecasts for the U.S. West and East Coasts.

MIT Sea Grant-funded researchers used a coupled physical-biogeochemical-acidification model to perform simulations and Bayesian learning of OA in Massachusetts Bay. MIT Sea Grant also funded the creation of a new web application to model OA in Massachusetts Bay and Stellwagen Bank. MIT Sea Grant-funded researchers continued development of a new autonomous coastal OA sensor system to measure pH and pCO_2 over a larger area.

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 a new buoy that acts in a collaborative, autonomous swarm to monitor OA over large areas. MIT Sea Grant also funded the creation of a biomimetic sensor to measure flow, which will benefit projects on OA to a proposed new area of aquaculture.

A project jointly funded by NOAA and DFO worked to share and refine respirometric methods useful for CO_2 effects studies.

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

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.

NOAA funded a regional vulnerability assessment to assess the vulnerability of the Atlantic sea scallop fishery using regional projections and to develop recommendations to management to assist the industry in adapting to projected OA and temperature changes. NOAA funded a project to expand understanding of multistressors on surfclams and provide both existing farmers and the surfclam fishing sector with data for farm-scale business planning. NOAA also funded a project to test the efficacy of different diet regimes to increase the resiliency of blue mussels to OA and warming, and to test for an interaction between diet enhancement and seawater buffering on laboratory and commercial scales.

New Jersey Sea Grant is funding a project to assess and improve the resilience of New Jersey's commercial fishing industry to climate change impacts.

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

The EPA conducted a project to assist a network of community scientists to measure coastal acidification variability in estuaries in New England by providing high-quality, and more affordable, new technology to community scientist organizations. Researchers from EPA (Office of Research and

Development and Region 1) worked together to develop and validate field-deployable total pH meters that can ultimately be utilized by participatory science groups. Organizations measured pH and collected water samples for TA to help estimate levels of carbonate saturation in coastal waters. This work culminated in a proof-of-concept report.

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.

Connecticut Sea Grant funded a new extension educator to accelerate technology transfer from the NOAA Milford Lab to the aquaculture industry in the North Atlantic, and to ensure industry priorities guide future research. MIT Sea Grant involved students in collaborative regional efforts and community science initiatives to communicate progress and knowledge gaps in OA. MIT Sea Grant also provided hands-on workshops on OA for K-12 students and teachers and communicated ocean and coastal acidification research through webinars and presentations.

United States Mid-Atlantic

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.[7] The study included characterization of water column carbonate chemistry and 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 the vulnerability of these coastal waters to acidification. The EPA continued to participate in the Mid-Atlantic Regional Ocean Council, specifically the monitoring work group to develop a regional monitoring infrastructure framework. 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 continued operating an OA mooring at the mouth of the Chesapeake Bay at First Landing in Virginia. NOAA funded a project to ensure that pH data collected by gliders operated by Rutgers University was integrated into the U.S. Integrated Ocean Observing System (IOOS) data products.

NOAA funded carbon chemistry sampling during four 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.

[7] https://www.boem.gov/sites/default/files/environmental-stewardship/Environmental-Studies/Atlantic/Biological/AT-17-06.pdf

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

NOAA funded a modeling project at Virginia Institute of Marine Sciences to identify the OA threshold that results in harmful impacts to Eastern oysters and whether meadows of underwater eelgrass can mitigate these impacts. NOAA also funded researchers from the University of Maryland, University of Delaware, and Oregon State University to study the relationship between biogeochemical cycling of carbon, oxygen, and nutrients, oyster growth and survival, and oyster economic profitability in the Chesapeake Bay; this will inform future vulnerability of aquaculture and wild oyster populations to OA. NOAA used a high-resolution regional ocean-biogeochemistry model to study the U.S. 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 region's first three NOAA-supported synoptic OA cruises.

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

Work continued on a NOAA-funded modeling project focused on the Chesapeake Bay, which 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. NOAA funded a new project to assess the vulnerability of the oyster aquaculture industry and oyster restoration to OA and other co-stressors and to produce information that will inform adaptation.

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 also hosted a "Hooked on Ocean Acidification" mini-series that connected recreational anglers, educators, managers, and regional scientists.

United States Southeast and Gulf Coast

Theme 1. Research to Understand Responses to Ocean Acidification

The EPA published a paper titled, *Elevated pCO_2 and hypoxia alter the acid-base regulation of developing sheepshead minnows Cyprinodon variegatus*, which described the results of biological response experiments focusing on the combined effects of coastal acidification on marine organisms conducted at its research laboratory in Gulf Breeze, Florida.[8]

[8] Enzor, L. A., Hankins, C., Hamilton-Frazier, M., Moso, E., Raimondo, S., & Barron, M. G. (2020). Elevated pCO2 and hypoxia alter the acid-base regulation of developing sheepshead minnows Cyprinodon variegatus. *Marine ecology progress series*, *636*, 157-168.

Through the National Coral Reef Monitoring Program, 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.

Georgia Sea Grant supported research on the role of sediments in the susceptibility to OA in coastal habitats. Louisiana Sea Grant supported research on the sensitivity of benthic species at artificial reefs to OA and warming and research on the impacts of eutrophication-driven OA on oyster health. Texas Sea Grant funded research on the role of freshwater on OA in estuaries in the northwest Gulf of Mexico and on past and present OA at coral reefs at Flower Garden Banks National Marine Sanctuary.

NSF funded a project examining the complex interplay of OA and sediment carbon chemistry on river-dominated continental margins, and another examining the impacts of stressors, including OA, on sponge bioerosion of oyster reefs.

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 conducted field activities in the Florida Keys to locate and map mangrove coral habitats that may serve as a refuge for reef-building corals from climate change and coastal acidification.

Theme 2. Monitoring of Ocean Chemistry and Biological Impacts

BOEM and NOAA continued a project to establish the Flower Garden Banks National Marine Sanctuary as a coral reef OA sentinel site. The project conducted chemical and biological monitoring to assess the health and vitality of the hermatypic coral reefs, evaluate water quality parameters, and provide an analysis of the status of the coral reefs in comparison with historical data.

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 information to improve understanding of vulnerability of coastal waters to coastal acidification. The Mobile Bay National Estuary Program began planning a new coastal acidification monitoring program in FY 2021.

In 2021, NOAA conducted the fourth Gulf of Mexico Ecosystems and Carbon Cruise, which occur every three to four years. The cruise sampled OA parameters, in addition to collecting plankton, environmental DNA (eDNA), and sediment core samples. NOAA scientists also continued analyzing data from previous synoptic cruises. NOAA also renewed a collaboration with select National Parks to complement near-shore data collection on the Northern Gulf of Mexico and East Coast. NOAA also added an underway TA system on the NOAA ship *Ronald H. Brown*, which collected data during the West Coast and Gulf of Mexico synoptic cruises. NOAA funded the addition of carbonate measurements to the harmful algal bloom monitoring cruises conducted on the Western Florida shelf.

NOAA operated a mooring at the Gray's Reef, off the coast 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 and an OA mooring deployed in coastal Louisiana. NOAA

monitored the progression and impacts of OA at multiple coral reef sites as a part of the National Coral Reef Monitoring Program, including Southeast Florida, the Florida Keys, and Dry Tortugas. A mission to Flower Garden Banks was delayed due to COVID-19 and did not occur in FY 2020-2021.

NOAA also funded an observing optimization study in the Northwest Gulf of Mexico that is using a combination of monitoring through gliders and fixed sensors and modeling to inform where additional monitoring is needed.

NSF provided continuing support for 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

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 U.S. 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 region's first three synoptic OA cruises. NOAA also funded development of an algorithm to determine TA in the East and Gulf Coasts using observations from cruises and moorings.

Louisiana Sea Grant funded research to use a model to assess the impact of river diversion and air-sea CO_2 exchange on coastal acidification.

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. NOAA also funded a project to investigate the effects of brackish water under different alkalinity regimes, OA conditions, and salinities on the survival and development of larval eastern oysters in hatcheries.

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

NOAA along with the Southeast and Gulf of Mexico Coastal Ocean Observing System Regional Associations continued to support 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 networks held town halls and webinars to engage members.

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

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 OA 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. NOAA funded a project to document the impact of major *Sargassum* biomass on reefs, including the resulting microbial activity and enhancement of OA.

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. NOAA supported an OA mooring at a La Parguera, Puerto Rico coral reef site. The National Coral Reef Monitoring Program's planned monitoring missions to non-sentinel coral reef sites in Puerto Rico and the United States Virgin Islands (St. John, St. Thomas, and St. Croix) were canceled due to COVID-19. Contractors were hired to do a subset of the work, some of which was completed at Puerto Rico sites in FY 2021. IOOS also funded OA monitoring at Jobos Bay National Estuarine Research Reserve (NERR).

The USGS continued 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, DIC, pCO_2, temperature, and salinity for the Caribbean Sea and Gulf of Mexico. NOAA also supported synthesis of NOAA-collected OA observations at coral reefs to better understand reef-scale biogeochemical processes and better link projection models of oceanic carbonate systems to reef-scale OA impacts.

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

NOAA funded a new project to design a framework for an OA vulnerability assessment in Puerto Rico through stakeholder interviews, synthesis, and a regional workshop.

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

NOAA's project to design a framework for a vulnerability assessment in Puerto Rico also began background work to establish a Caribbean Coastal Acidification Network. The goal is that this would be a new sustained coastal acidification network to engage scientists, government employees, industry members, and other stakeholders in the region.

United States West Coast

Theme 1. Research to Understand Responses to Ocean Acidification

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 one of the response metrics. These mesocosm experiments elucidate the role of seagrass and macroalgae in moderating acidification.

NOAA improved its facilities for conducting species response to OA and climate change experiments at the Northwest Fisheries Science Center Montlake Laboratory (Seattle, Washington) and Manchester Laboratory (Port Orchard, Washington). The Mukilteo Laboratory operated by the Northwest Fisheries Science Center was permanently closed. NOAA scientists studied Dungeness crab; coho, pink and Chinook salmon; sablefish; and krill under OA conditions, often conducting OA experiments with stressors expected to co-occur with OA (e.g., high temperature). Some experiments also considered the potential for acclimation and adaptation. NOAA also conducted a project comparing bacterial and phytoplankton community structure to water chemistry in the Northern California Current during upwelling and OA conditions to understand the response of the food web base and potentially identify a microbial indicator for OA. Much lab work was delayed due to COVID-19 restrictions and was unable to occur during FY 2020-2021.

California Sea Grant supported projects to study if culturing red abalone and seaweed together can ameliorate the negative impacts of OA, to study the effects of OA on red abalone both within and across generations, and to study the genetic potential for the Pacific oyster to adapt to OA and hypoxia. The University of Southern California Sea Grant funded research on the effects of OA and hypoxia larval Dungeness crab and red sea urchin.

NOAA funded a collaborative project using oceanographic measurements, field work, and lab experiments to study diploid and triploid oysters' physiological tolerance and survival under multiple stressors. NOAA and DFO funded a joint project to evaluate the sensitivity of larval Dungeness crab to OA from populations in Washington and British Columbia.

NSF funded a project examining OA's effects on natural selection patterns in two coastal fishes. Another NSF project examines ecosystem metabolism in rocky intertidal communities of southern California under warming and acidifying conditions.

Theme 2. Monitoring of Ocean Chemistry and Biological Impacts

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 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 interact with natural events to exacerbate the magnitude and duration of coastal acidification and hypoxia in these estuarine habitats.

In 2021, NOAA conducted the sixth West Coast Ocean Acidification Cruise, which sampled ocean acidification parameters at 133 stations between Canada and Southern California.

NOAA operated coastal OA moorings in Washington, Oregon, and Southern California, and an open-ocean OA mooring off southern California. NOAA also monitored OA at the Olympic Coast National Marine Sanctuary (Washington). NOAA maintained 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, and on the R/V *Thompson* and M/V *Bluefin*. Data were reduced during FY 2020 due to COVID-19 restrictions.

NOAA scientists began a new project to carry out CO_2 measurements in coordination with the California Cooperative Oceanic Fisheries Investigation program, which collects important biological data. IOOS funded the South Slough NERR to refurbish OA sensors. IOOS also funded additional OA monitoring at stations throughout California. NOAA and IOOS supported OA monitoring at shellfish

aquaculture sites along the West Coast, meeting industry's information needs and gathering data on how OA is expressed in nearshore waters.

NOAA also funded an observing system optimization study to assess how well current monitoring platforms represent regional exposure to OA along the central and Northern California coast and to identify improvement opportunities.

The Coastal Endurance Array, an element of NSF's OOI, 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, contributing support for OA-related measurements, and OA-related observations and ship time at the California Current Ecosystem LTER site.

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 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 DIC, TA, pH, oxygen, and calcite/aragonite saturation twice a year, and is being extended to forecast impacts on Dungeness crab.

NOAA funded lab experiments on Dungeness crab to inform a forecast of pre-juvenile life stage abundance under the Joint Institute for the Study of the Atmosphere and Ocean Seasonal Coastal Ocean Prediction of the Ecosystem (J-SCOPE). NOAA scientists are also working to develop individual-based models and population models for krill that link individual responses to OA, warming, and deoxygenation to changes at the population level.

Oregon Sea Grant funded expanded data collection to support a model identifying habitat suitability for oysters under OA.

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 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

Work continued on NOAA-funded regional vulnerability assessments to assess the socio-cultural vulnerability and resilience of Tribal and non-Tribal coastal communities to OA in Washington and understand the vulnerability and adaptation to OA among Pacific Northwest mussel and oyster stakeholders. A new regional vulnerability assessment was funded to assess the vulnerability of coastal communities in California and Oregon to OA, how they adapt, and to evaluate the barriers to coping to inform policy.

The Ocean Acidification Sentinel Site (OASeS) on the Olympic Coast of Washington state continued to operate as an Olympic Coast National Marine Sanctuary Advisory Council Working Group. The

OASeS focuses on OA-related science and identifies trends in carbonate chemistry and hypoxia. It informs resource managers and coastal communities by telling the story of OA and its impacts on Washington coastal marine resources, coastal cultures, communities, and economies. The OASeS seeks to ensure that the Olympic Coast is well prepared for changing ocean conditions, with research and management actions in place.

NOAA scientists served as members of the California Ocean Acidification and Hypoxia Task Force, which provided 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, which maintains a sustainable and coordinated focus on OA.

NOAA funded a project to develop resilience to OA in the Pacific Northwest shellfish aquaculture industry by comparing the sensitivities of the native littleneck clam and non-native, commercially important Manila clam, exploring the molecular mechanisms underlying parental carryover effects, and getting buy-in from the industry and regulators. Most work was delayed due to COVID-19 restrictions and did not occur in FY 2020-2021.

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

EPA continues to participate on the Oregon Ocean Acidification and Hypoxia (OAH) Monitoring group (formed as part of the Oregon Coordinating Council on Ocean Acidification and Hypoxia), which focuses on developing plans for acidification monitoring and coordinating monitoring by state and federal agencies.

NOAA continued to support the California Current Acidification Network, a collaboration of interdisciplinary scientists, resource managers, industry members, and representatives from local, state, and Tribal governments.

Oregon Sea Grant created a website for their Meaningful Watershed Educational Experiences, which includes resources on OA for educators. Washington Sea Grant's OA specialist conducted education and outreach activities.

Theme 7. Data Management, Integration, and Synthesis

IOOS continued operating a dedicated website to serve OA chemistry data from various observing assets along the U.S. West Coast, Alaska, and U.S. Pacific Islands region. This website facilitates the transfer of observing data from scientists to regional and national stakeholders.

NOAA funded the analysis of chemical and biological data sets to estimate the time horizon for detecting biological effects, with the goal of informing the design of sampling programs.

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, Oregon 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, and snow crab. Alaska Sea Grant funded projects to determine the physiological responses of juvenile basket cockles and littleneck clams to OA.

DFO and NOAA funded a joint project to study Arctic cod responses to increased temperature and OA across life stages.

NSF provided continuing support for a five-year award on ecosystem impacts of OA and other stressors on kelp forests in southeast Alaska.

Theme 2. Monitoring of Ocean Chemistry and Biological Impacts

BOEM continued funding a study that deployed oceanographic SeapHOx sensors along a Cook Inlet freshwater gradient. The study aims to establish baseline measurements and to quantify the sources of pH variability, and results 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 Bering Sea buoy was taken in for repairs in 2019, and redeployment was delayed from 2020 to 2021 due to COVID-19. The Alaska Ocean Observing System (AOOS) continued sentinel monitoring in the Cook Inlet, contributing to developing risk assessment tools for OA. AOOS also supports OA sampling cruises along the Seward Line in the northern Gulf of Alaska in partnership with the University of Alaska. 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 comprising Alaska's marine waters. As noted 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. Planning continued for a Gulf of Alaska synoptic OA cruise, which was delayed from 2020 to 2022 due to the COVID-19 pandemic; as a replacement, gliders collected pH and phytoplankton data in the Gulf of Alaska. NOAA funded installation of "Burke-o-Lators" to measure carbonate chemistry parameters in Seward, Ketchikan, Sitka, and Kodiak in support of community-based OA monitoring.

Alaska Sea Grant funded researchers to characterize the seasonal fluctuations of carbon dioxide in nearshore coastal environments in Kachemak Bay and Juneau.

NOAA supported increased chemical monitoring and eDNA samples coordinated with fisheries ecosystem monitoring, to support the development of an OA ecosystem indicator to be included in the NOAA Ecosystem Status Report for the Bering Sea.

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

NOAA supported incorporating 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, exploring different crab management strategies.

NOAA supported modeling the direct and indirect effects of OA on Pacific cod in the Bering Sea, to refine existing fisheries recruitment models. NOAA funded a project to assess the ability of a model to forecast OA conditions in the Bering Sea, which will inform development of a product for fisheries managers to be used in the Ecosystems Status Report. In FY 2021, NOAA scientists built off this work by starting a project to expand the model hindcast, conduct retrospective forecast for 2017-2019, and to compare model forecast skill to observations. NOAA also developed linked bioeconomic models to forecast effects of OA on commercially important stocks of Alaska crab and groundfish.

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 funded a regional vulnerability assessment to understand OA threats to traditional and coastal Alaska industries in south-central and southeast Alaska to develop decision support tools to incorporate OA into localized socio-ecological systems.

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 hosted webinars to share different research results with community members.

United States Pacific Islands

Theme 1. Research to Understand Responses to Ocean Acidification

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 and carbonate budgets.

NSF funded a new study of net ecosystem calcification on coral reefs using mesocosm experiments in Hawai'i. A continuing project examines the susceptibility of deep-sea corals to ocean acidification in the Northwestern Hawaiian Islands and Emperor Seamount Chain.

USGS continued 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, Hawai'i.

Theme 2. Monitoring of Ocean Chemistry and Biological Impacts

NOAA and Hawai'i Sea Grant operated four coral-reef OA moorings off Oahu, Hawai'i. NOAA also operated open-ocean OA moorings off Hawai'i and Japan in the Kuroshio Extension current, along with a mooring 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. A monitoring cruise to the Marianas Archipelago as part of the National Coral Reef Monitoring Program was canceled due to COVID-19 in FY 2020 and FY 2021. Shore-based monitoring at sites in Oahu was able to take place. NOAA also continued collaborating on capacity-building efforts for increased regional monitoring in the Pacific Islands through work funded by the Department of State and The Ocean Foundation.

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 to better understand reef-scale biogeochemical processes and 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, Hawai‘i.

As a part of the previously mentioned NSF-funded study of net ecosystem calcification, the project is also developing a new solid-state sensor to measure alkalinity and pH.

Theme 5. Assessment of Socioeconomic Impacts and Development of Strategies to Conserve Marine Organisms and Ecosystems
NOAA funded a vulnerability assessment using OA climate, regional, and coral reef ecosystem models and satellite assessments to link the state of coral ecosystems with societal outcomes in the Hawaiian Archipelago.

Arctic

Theme 2. Monitoring of Ocean Chemistry and Biological Impacts
NOAA and BOEM 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 funded 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 also operated an OA mooring in the North Atlantic off Iceland.

Theme 3. Improving Models of the Effects of Ocean Acidification on Ecosystems and Society
DFO and NOAA funded a joint project to model the impacts of Bering Sea OA patterns on the Bering Strait inflow into the Arctic.

Antarctic

Theme 2. Monitoring of Ocean Chemistry and Biological Impacts
NSF continued supporting observations in coastal waters of the Antarctic Peninsula at the Palmer Antarctic LTER site.

Appendix A

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

Theme	FY 2020 Actual ($K)	FY 2021 Actual ($K)	Activity Classification
1. Research to understand responses to ocean acidification	3,099	2,889	Contributing
	6,429	9,765	Primary
	9,528	12,654	Total
2. Monitoring of ocean chemistry and biological impacts	61,738	68,679	Contributing
	5,662	7,859	Primary
	67,400	76,538	Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms	826	311	Contributing
	2,867	2,241	Primary
	3,693	2,552	Total
4. Technology development and standardization of measurements	1,792	367	Contributing
	1,516	2,684	Primary
	3,308	3,050	Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems	517	107	Contributing
	3,276	663	Primary
	3,793	770	Total
6. Education, outreach, and engagement on ocean acidification	160	128	Contributing
	1,031	619	Primary
	1,191	747	Total
7. Data management and integration	4,728	4,109	Contributing
	859	791	Primary
	5,587	4,900	Total
8. Other ocean acidification research and monitoring activities	0	1,000	Contributing
	2,156	5,154	Primary
	2,156	6,154	Total
Total	72,860	77,590	Total Contributing
	23,795	29,774	Total Primary
	96,656	107,365	Grand Total

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

Theme	FY 2020 Actual ($K)	FY 2021 Actual ($K)	Activity Classification
1. Research to understand responses to ocean acidification	0	0	Contributing
	0	0	Primary
	0	0	Total
2. Monitoring of ocean chemistry and biological impacts	791	21	Contributing
	120	77	Primary
	911	99	Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms	0	0	Contributing
	0	0	Primary
	0	0	Total
4. Technology development and standardization of measurements	0	0	Contributing
	0	0	Primary
	0	0	Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems	0	0	Contributing
	0	0	Primary
	0	0	Total
6. Education, outreach, and engagement on ocean acidification	0	0	Contributing
	0	0	Primary
	0	0	Total
7. Data management and integration	0	0	Contributing
	0	0	Primary
	0	0	Total
8. Other ocean acidification research and monitoring activities	0	0	Contributing
	0	446	Primary
	0	446	Total
Total	791	21	Total Contributing
	120	523	Total Primary
	911	544	Grand Total

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

Theme	FY 2020 Actual ($K)	FY 2021 Actual ($K)	Activity Classification
1. Research to understand responses to ocean acidification	0	0	Contributing
	89	125	Primary
	89	125	Total
2. Monitoring of ocean chemistry and biological impacts	0	0	Contributing
	181	135	Primary
	181	135	Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms	0	0	Contributing
	0	0	Primary
	0	0	Total
4. Technology development and standardization of measurements	0	0	Contributing
	0	0	Primary
	0	0	Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems	0	0	Contributing
	0	0	Primary
	0	0	Total
6. Education, outreach, and engagement on ocean acidification	0	0	Contributing
	0	0	Primary
	0	0	Total
7. Data management and integration	0	0	Contributing
	0	0	Primary
	0	0	Total
8. Other ocean acidification research and monitoring activities	0	0	Contributing
	0	0	Primary
	0	0	Total
Total	0	0	Total Contributing
	270	260	Total Primary
	270	260	Grand Total

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

Theme	FY 2020 Actual ($K)	FY 2021 Actual ($K)	Activity Classification
1. Research to understand responses to ocean acidification	380	400	Contributing
	0	0	Primary
	380	400	Total
2. Monitoring of ocean chemistry and biological impacts	0	0	Contributing
	150	150	Primary
	150	150	Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms	250	250	Contributing
	0	0	Primary
	250	250	Total
4. Technology development and standardization of measurements	0	200	Contributing
	0	0	Primary
	0	200	Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems	40	40	Contributing
	0	0	Primary
	40	40	Total
6. Education, outreach, and engagement on ocean acidification	0	0	Contributing
	100	100	Primary
	100	100	Total
7. Data management and integration	0	0	Contributing
	0	0	Primary
	0	0	Total
8. Other ocean acidification research and monitoring activities	0	0	Contributing
	0	0	Primary
	0	0	Total
Total	670	890	Total Contributing
	250	250	Total Primary
	920	1140	Grand Total

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

Theme	FY 2020 Actual ($K)	FY 2021 Actual ($K)	Activity Classification
1. Research to understand responses to ocean acidification	0	0	Contributing
	60	60	Primary
	60	60	Total
2. Monitoring of ocean chemistry and biological impacts	0	0	Contributing
	0	0	Primary
	0	0	Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms	0	0	Contributing
	0	0	Primary
	0	0	Total
4. Technology development and standardization of measurements	0	0	Contributing
	85	85	Primary
	85	85	Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems	0	0	Contributing
	0	0	Primary
	0	0	Total
6. Education, outreach, and engagement on ocean acidification	0	0	Contributing
	0	0	Primary
	0	0	Total
7. Data management and integration	0	0	Contributing
	0	0	Primary
	0	0	Total
8. Other ocean acidification research and monitoring activities	0	0	Contributing
	0	0	Primary
	0	0	Total
Total	0	0	Total Contributing
	145	145	Total Primary
	145	145	Grand Total

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

Theme	FY 2020 Actual ($K)	FY 2021 Actual ($K)	Activity Classification
1. Research to understand responses to ocean acidification	1,071	958	Contributing
	2,442	4,901	Primary
	3,514	5,860	Total
2. Monitoring of ocean chemistry and biological impacts	5,270	4,051	Contributing
	5,211	7,497	Primary
	10,481	11,548	Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms	576	61	Contributing
	2,831	2,203	Primary
	3,407	2,264	Total
4. Technology development and standardization of measurements	1792	167	Contributing
	391	487	Primary
	2,183	653	Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems	233	67	Contributing
	3,276	663	Primary
	3,509	730	Total
6. Education, outreach, and engagement on ocean acidification	50	128	Contributing
	853	241	Primary
	903	369	Total
7. Data management and integration	334	334	Contributing
	859	791	Primary
	1,193	1,125	Total
8. Other ocean acidification research and monitoring activities	0	0	Contributing
	2,156	4,708	Primary
	2,156	4,708	Total
Total	9,327	5,765	Total Contributing
	18,019	21,491	Total Primary
	27,346	27,256	Grand Total

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

Theme	FY 2020 Actual ($K)	FY 2021 Actual ($K)	Activity Classification
1. Research to understand responses to ocean acidification	60	50	Contributing
	3,639	4,430	Primary
	3,699	4,480	Total
2. Monitoring of ocean chemistry and biological impacts	55,322	64,394	Contributing
	0	0	Primary
	55,322	64,394	Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms	0	0	Contributing
	36	38	Primary
	36	38	Total
4. Technology development and standardization of measurements	0	0	Contributing
	1,040	2,112	Primary
	1,040	2,112	Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems	0	0	Contributing
	0	0	Primary
	0	0	Total
6. Education, outreach, and engagement on ocean acidification	60	0	Contributing
	78	278	Primary
	138	278	Total
7. Data management and integration	4,394	3,775	Contributing
	0	0	Primary
	4,394	3,775	Total
8. Other ocean acidification research and monitoring activities	0	0	Contributing
	0	0	Primary
	0	0	Total
Total	59,836	68,220	Total Contributing
	4,793	6,857	Total Primary
	64,629	75,077	Grand Total

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

Theme	FY 2020 Actual ($K)	FY 2021 Actual ($K)	Activity Classification
1. Research to understand responses to ocean acidification	1,099	1,099	Contributing
	0	0	Primary
	1,099	1,099	Total
2. Monitoring of ocean chemistry and biological impacts	0	0	Contributing
	0	0	Primary
	0	0	Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms	0	0	Contributing
	0	0	Primary
	0	0	Total
4. Technology development and standardization of measurements	0	0	Contributing
	0	0	Primary
	0	0	Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems	0	0	Contributing
	0	0	Primary
	0	0	Total
6. Education, outreach, and engagement on ocean acidification	0	0	Contributing
	0	0	Primary
	0	0	Total
7. Data management and integration	0	0	Contributing
	0	0	Primary
	0	0	Total
8. Other ocean acidification research and monitoring activities	0	1,000	Contributing
	0	0	Primary
	0	1,000	Total
Total	1,099	2,099	Total Contributing
	0	0	Total Primary
	1,099	2,099	Grand Total

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

Theme	FY 2020 Actual ($K)	FY 2021 Actual ($K)	Activity Classification
1. Research to understand responses to ocean acidification	489	382	Contributing
	198	248	Primary
	688	630	Total
2. Monitoring of ocean chemistry and biological impacts	355	213	Contributing
	0	0	Primary
	355	213	Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms	0	0	Contributing
	0	0	Primary
	0	0	Total
4. Technology development and standardization of measurements	0	0	Contributing
	0	0	Primary
	0	0	Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems	244	0	Contributing
	0	0	Primary
	244	0	Total
6. Education, outreach, and engagement on ocean acidification	50	0	Contributing
	0	0	Primary
	50	0	Total
7. Data management and integration	0	0	Contributing
	0	0	Primary
	0	0	Total
8. Other ocean acidification research and monitoring activities	0	0	Contributing
	0	0	Primary
	0	0	Total
Total	1,138	595	Total Contributing
	198	248	Total Primary
	1,336	843	Grand Total