EIGHTH REPORT ON FEDERALLY FUNDED OCEAN ACIDIFICATION RESEARCH AND MONITORING ACTIVITIES

A Report by the

INTERAGENCY WORKING GROUP ON OCEAN ACIDIFICATION

of the

SUBCOMMITTEE ON OCEAN SCIENCE AND TECHNOLOGY

COMMITTEE ON ENVIRONMENT

of the

NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

December 2024

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 NSTC Group Name

The National Science and Technology Council (NSTC) was established by Executive Order on November 23, 1993. This Cabinet-level Council is the principal means within the executive branch to coordinate science and technology policy across the diverse entities that make up the federal research and development enterprise. Chaired by the President, the membership of the NSTC is made up of the Vice President, the Director of the OSTP, Cabinet Secretaries and Agency Heads with significant science and technology responsibilities, and other White House officials.

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.

Disclaimer

References in this document to any specific commercial products, publications, processes, services, manufacturers, companies, trademarks, or other proprietary information are intended to provide clarity and do not constitute an endorsement or recommendation by the U.S. government.

Copyright Information

NATIONAL SCIENCE and TECHNOLOGY COUNCIL

Chair

Arati Prabhakar, Assistant to the President for Science and Technology; Director, OSTP

Executive Director (Acting)

Lisa E. Friedersdorf, OSTP

COMMITTEE ON ENVIRONMENT

Co-Chairs

Chris Frey, EPA
Jane Lubchenco, OSTP
Richard Spinrad, DOC/NOAA

SUBCOMMITTEE ON OCEAN SCIENCE AND TECHNOLOGY

Co-Chairs

Tom Drake, ONR
Danielle Farelli, OSTP
Alexandra Isern, NSF
Steven Thur, DOC/NOAA

Executive Secretary

Raquel Gilliland, DOC/NOAA
Victoria Moreno, DOC/NOAA
Elaine Shen, NSF

INTERAGENCY WORKING GROUP ON OCEAN ACIDIFICATION

Chair

Sarah Cooley, DOC/NOAA

Executive Secretary

Courtney Witkowski, DOC/NOAA

Members

Krisa Arzayus, DOC/NOAA
Kelsey Bisson, NASA
Christina Bonsell, DOI/BOEM
Cheryl Brown, EPA
Shallin Busch, DOC/NOAA
Meaghan Cuddy, Department of State
Eva DiDonato, DOI/NPS
Regina Easley, DOC/NIST
Henrietta Edmonds, NSF
Richard Feely, DOC/NOAA
Dwight Gledhill, DOC/NOAA
Patrick Hogan, DOC/NOAA
Alyse Larkin, DOC/NOAA
Pete Leary, DOI/FWS
Laura Lorenzoni, NASA
Whitman Miller, SI
Amanda Reynolds, SI
Caird Rexroad, USDA
Kaushlendra Tingi, USDA
Jason Waters, DOC/NIST
Katherine Weiler, EPA
Kim Yates, DOI/USGS

Table of Contents

Abbreviations and Acronyms

AOAN	Alaska Ocean Acidification Network
BGC	biogeochemical
BOEM	Bureau of Ocean Energy Management
CalCOFI	California Cooperative Oceanic Fisheries Investigation
CANs	Coastal Acidification Networks
CFOAM	Center for Ocean Acidification Monitoring
CGEM	Coastal Generalized Ecosystem Model
CLIVAR	Climate and Ocean: Variability, Predictability and Change
CMIP6	Coupled Model Intercomparison Project 6th Phase
CO_2	carbon dioxide
DFO	Fisheries and Oceans Canada
DIC	dissolved inorganic carbon
DMS	Data Management Synthesis
DOC	Department of Commerce
DOI	Department of Interior
EcoMon	Ecosystems Monitoring Cruises
eDNA	environmental DNA
EPA	Environmental Protection Agency
fCO_2	fugacity of carbon dioxide
FOARAM	Federal Ocean Acidification Research and Monitoring
FWS	Fish and Wildlife Service
FY	fiscal year
GCAN	Gulf of Mexico Coastal Acidification Network
GHG	greenhouse gases
GLIMR	Geosynchronous Littoral Imaging and Monitoring Radiometer
GOA-ON	Global Ocean Acidification Observing Network
GO-SHIP	Global Ocean Ship-based Hydrographic Investigation Program
HABs	harmful algal blooms
IWG-OA	Interagency Working Group on Ocean Acidification
JISAO	Joint Institute for the Study of the Atmosphere and the Ocean
LNE	Laboratoire National de Métrologie et d'Essais
LTER	Long Term Ecological Research
MACAN	Mid-Atlantic Coastal Acidification Networks
mCDR	marine carbon dioxide removal
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
NCRMP	National Coral Reef Monitoring Program
NECAN	Northeast Coastal Acidification Network
NEFSC	Northeast Fisheries Science Center
NEPs	National Estuary Programs
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NOPP	National Oceanographic Partnership Program
NPS	National Park Service
NSF	National Science Foundation
NSTC	National Science and Technology Council
NWFSC	Northwest Fisheries Science Center
OA	ocean acidification

OAE	ocean alkalinity enhancement
OAIE	Ocean Acidification Information Exchange
OAP	Ocean Acidification Program
OASeS	Ocean Acidification Sentinel Site
OCADS	Ocean Carbon and Acidification Data System
ONR	Office of Naval Research
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
RMs	reference materials
SBG	Surface Biology and Geology
SI	Smithsonian Institution
SOCAN	Southeast Ocean and Coastal Acidification Network
SOCAT	Surface Ocean CO_2 Atlas
SWFSC	Southwest Fisheries Science Center
TA	total alkalinity
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WHOI	Woods Hole Oceanographic Institution

Executive Summary

Ocean acidification (OA) is the reduction in seawater pH driven by anthropogenic carbon dioxide (CO_2) emissions. OA has the potential to negatively impact marine species and ecosystems, which could have negative socioeconomic and cultural impacts for the coastal communities that rely on these resources. As part of the Biden-Harris Administration's commitment to deliver on the most ambitious climate and conservation agenda in history, the government has advanced OA research and monitoring as outlined in the Ocean Climate Action Plan and the United States Ocean Acidification Action Plan.

The Interagency Working Group on Ocean Acidification (IWG-OA) coordinates OA research and monitoring across federal agencies and implements the Strategic Plan for Federal Research and Monitoring of Ocean Acidification. This report describes all OA actions funded by the federal government in fiscal years 2022 and 2023, including actions primarily focused on OA and actions that are contributing, meaning they had a broader focus but still provided information relevant to measuring or understanding OA. During this timeframe, the federal government spent $51.8 million on primary actions and $175.5 million on contributing actions. Researchers, resource managers, and educators are using these significant investments to further our understanding of the impacts of OA to marine ecosystems and help prepare coastal communities to prepare and adapt.

This report describes the funded OA actions, organized by geographical scope, then by the seven thematic areas of the Strategic Plan, and lastly by agency. OA actions were funded by nine federal agencies: the Bureau of Ocean and Energy Management (BOEM), the Environmental Protection Agency (EPA), the National Aeronautics and Space Administration (NASA), the National Institute for Standards and Technology (NIST), the National Oceanic and Atmospheric Administration (NOAA), the National Park Service (NPS), the Department of Agriculture (USDA), the Geological Survey (USGS), the National Science Foundation (NSF).

Funded actions both sustained ongoing OA monitoring and research and made new progress to addressing the research priorities identified in the Strategic Plan. The following is a short overview of the seven thematic areas in the Strategic Plan and how agencies worked to address priorities within each theme:

- **Research:** Agencies funded research on the occurrence and effects of OA in combination with other environmental stressors and effects on economically important species.
- **Monitoring:** OA data were collected via ships, moorings, and autonomous vehicles. Monitoring took place in sensitive ecosystems such as estuaries and coral reefs.
- **Modeling:** Improvements to biogeochemical models allow for better long-term predictions and short-term forecasts of OA conditions. OA was also integrated into ecological and socioeconomic models to predict impacts to species and communities.
- **Technology and Standards:** Agencies invested in developing new sensors to measure OA. They also worked to ensure the availability of reference materials, which are used to standardize OA measurements of seawater samples and ensure data quality.
- **Socioeconomic Impact:** A number of projects assessed the vulnerability of specific industries and communities and informed mitigation and adaptation strategies.
- **Education and Outreach:** Agencies engaged with stakeholders through a number of forums and also funded development of OA curriculum for students.

- **Data Management and Synthesis:** Investments in OA data management continued to ensure that data is publicly available and quality controlled.

These investments make significant progress on the ocean acidification strategic plan.

Introduction

OA is the reduction in seawater pH caused by the ocean's uptake of anthropogenic CO_2 from the atmosphere. This change in ocean chemistry harms marine species and ecosystems and threatens the value and services provided by the ocean to society. The Biden-Harris Administration has made it a priority to advance OA research and monitoring, as outlined in the Ocean Climate Action Plan and the United States Ocean Acidification Action Plan.

The Interagency Working Group on Ocean Acidification (IWG-OA) works to coordinate OA research and monitoring across federal agencies in response to the Federal Ocean Acidification Research and Monitoring Act of 2009. The priorities of the federal government are outlined in the Strategic Plan for Federal Research and Monitoring of Ocean Acidification. The second version of the Strategic Plan was published in 2023 and contains objectives and action items across seven themes: (1) research; (2) monitoring; (3) modeling; (4) technology development; (5) socioeconomic impacts; (6) education, outreach, and engagement strategies; and (7) data management and integration.

Every two years, the IWG-OA releases a biennial report documenting federal spending related to OA. This document is the eighth such report and summarizes federally funded OA activities for fiscal years (FY) 2022 and 2023, which represents the time period of October 1st, 2021 through September 30th, 2023. The report contains sections for global and national efforts, as well as nine regional sections. Each section describes funded OA actions, organized by the seven thematic areas of the IWG-OA Strategic Plan and then by federal agency. Some regions do not have actions for every thematic area.

The Appendix summarizes federal spending for OA research and monitoring activities by agency for each thematic area. 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 2022, federal agencies provided approximately $23.6 million toward activities with a primary focus on OA and an additional $71.5 million for contributing activities. In FY 2023, federal funding was approximately $28.1 million for primary activities and $52.2 million for contributing activities.

These investments supported research, monitoring, and outreach that will lead to a better assessment of the impacts of OA on marine ecosystems and coastal communities and support the development of mitigation and adaptation strategies. The funded actions both sustain ongoing work to monitor OA and research impacts to species, and make new progress in addressing the actions of the IWG-OA Strategic Plan. Of note is that this is the first report to record funding to the Great Lakes region, which now has active OA research and monitoring.

Additionally, marine carbon dioxide removal (mCDR) research has emerged as a new scientific priority. In 2022 and 2023, a suite of mCDR research projects were funded through the National Oceanographic Partnership Program (NOPP) in an interagency effort that leveraged private partners and funding from the Inflation Reduction Act. This report includes descriptions of projects funded through NOPP that also consider the potential and weigh the risks of mCDR to mitigate OA.

The following text highlights some significant work funded under each thematic area of the Strategic Plan in FY 2022 – 2023.

Research to Understand Responses to Ocean Acidification

Advancing research on the impacts of OA on marine ecosystems and ecologically and economically important species is critical to predicting future impacts from OA on our oceans. The

federal government funded research that considers OA in the context of other environmental stressors, which have the potential to occur in combination and amplify stresses on ecosystems; investigate impacts in estuaries and other vulnerable coastal habitats; and study the adaptation potential of ecologically and economically valuable species.

Monitoring of Ocean Chemistry and Biological Impacts

Agencies sustained operation of critical OA observing assets, including large-scale ship-based efforts, buoys and moorings, underway monitoring via ships of opportunity, and autonomous floats. Maintaining assets represents a significant cost, and some current technologies are facing obsolescence. A specific challenge is the lack of available vessels to implement scheduled cruises.

Agencies also funded a number of efforts to increase data collection in coastal ecosystems, through monitoring in estuaries, NPS sites, National Marine Sanctuaries, and coral reefs. OA data was also collected in partnership with a number of ongoing programs that collect biological data. Work continued to enable biogeochemistry monitoring from space via satellites.

Improving Models of the Effects of Ocean Acidification on Ecosystems and Society

Agencies continued funding global and regional biogeochemistry models that provide historical and future projections of OA on the decadal-scale, in addition to targeted local forecasts that provide shorter-term (3-day and seasonal) predictions. OA was also incorporated into ecosystem models and used to develop OA indexes used to inform fisheries management.

Other modeling projects were relevant to understanding OA vulnerability or mitigation. For example, models were funded to understand hazard mitigation services provided by natural seafloor infrastructure such as coral reefs, to understand the impacts of land-based pollution on coastal acidification, and to understand the impacts to fisheries via bioeconomic models. Projects were also funded to study the potential impacts of various mCDR techniques, such as iron fertilization and ocean alkalinity enhancement.

Technology Development and Standardization of Methods

Developing new carbon observing technologies remains a critical priority as the lack of adequate sensors is a major challenge for fully implementing our OA observing priorities. Projects were funded to develop new pH sensors, test a new sensor for buoys to measure multiple carbonate parameters, and integrate pH sensors onto gliders. Agencies also worked to determine low-cost alternatives for analyzing seawater OA samples.

Another major priority remained building a more resilient production model for carbon-in-seawater reference materials. Agencies funded the development of a standard operating procedure for producing secondary reference materials, and an interagency effort continued to establish NIST as a centralized certifier for future producers.

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

Understanding the vulnerability of coastal communities relies on OA monitoring, modeling, and research, but also requires additional social science research and synthesis. Funding continued for regional vulnerability assessments that analyze the vulnerability of specific communities or

industries and build support for mitigation and adaptation. Other funding supported evaluation of the impacts of OA on ecosystem services and fisheries or developed decision support tools for fisheries and the aquaculture industry.

Education, Outreach, and Engagement Strategy on Ocean Acidification

Agencies engaged partners and the public through a number of international, national, and regional conferences and outreach activities, including through the Global Ocean Acidification Observing Networks and the Coastal Acidification Networks. Funding supported the development of educational tools and curriculum specific to OA and provided training.

Data Management, Integration, and Synthesis

Agencies continued to support OA data management primarily at the national and global level through efforts such as the Surface Ocean CO_2 Atlas (SOCAT), the Data Management and Synthesis Project, and the Ocean Carbon and Acidification Data System (OCADS). These systems provide critical support to ensure that OA data are quality controlled and publicly available. New synthesis projects were funded to assess the impacts of greenhouse gases (GHGs) on OA and to develop OA indicators for different regions.

Activities by Geographical Region

The following sections detail the actions funded by each agency for certain geographical regions: Global, National, Northeast, Mid-Atlantic, Southeast and Gulf of Mexico, Caribbean, West Coast, Alaska, Great Lakes, Pacific Islands, and the Arctic.

Global

OA is driven primarily by global emissions of CO_2 and requires global engagement to address its causes, extent, and effects. As most federally funded research focuses on the local or regional scale, few projects are considered global in reach. However, several agencies do engage globally with the international community to share information and collaborate on research and monitoring. In addition, many research activities are general in nature or not tied to one of the specific regions highlighted later in this report.

Theme 1: Research to Understand Responses to Ocean Acidification

NASA continued the support of interdisciplinary research to investigate the processes contributing to the variability of OA and of the air-sea interactions, including the role of atmospheric deposition in enhancing phytoplankton blooms and carbon drawdown.

NASA continued its support of bio-optical measurements in the Southern Ocean from Biogeochemical Argo Floats with the goal of further understanding biogeochemical dynamics in this region and their link to biological productivity and satellite measurements.

NASA continued funding research on ocean biology and biogeochemistry, leveraging data from federal and commercial satellites with ocean observing capabilities and coupled in situ measurements. NASA funded efforts to reduce uncertainty in measurements of phytoplankton chlorophyll and several other ocean biology, ecology, and biogeochemistry data products retrieved from space.

NSF supported a new project to use novel carbon isotope tracer techniques to study calcium carbonate dissolution rates under different conditions in laboratory experiments.

NSF supported a new project investigating dissolution of calcium carbonate in sediments below the seafloor using global sediment samples in order to determine the importance of this process to seawater chemistry and the impacts of OA.

NSF provided ongoing support to a project that is developing a mathematical model of how organisms and ecosystems respond to natural fluctuations in and disturbances to their environment. This model can be used to explore responses to a variety of stressors, including OA.

NSF continued to support the Moorea Coral Reef Long Term Ecological Research (LTER) site in French Polynesia, where research included evaluating how OA will affect the structure and function of coral reefs.

NSF supported a new project aimed at quantifying the impact of the reaction of seawater with mantle rocks exposed at the seafloor and in hydrothermal systems on ocean chemistry. These reactions, broadly termed “serpentinization,” play a key role in determining the alkalinity balance of the ocean, and thus the ocean’s response to acidification.

Theme 2: Monitoring of Ocean Chemistry and Biological Impacts

NASA continued the development of the Plankton, Aerosol, Cloud, and ocean Ecosystem (PACE) satellite mission (which launched in February 2024), the Surface Biology and Geology (SBG) satellite mission, and the Geosynchronous Littoral Imaging and Monitoring Radiometer (GLIMR) instrument. These Earth Observing missions will significantly contribute to further understanding changes in ocean biogeochemical cycling and quantifying ecosystem function due to natural and anthropogenic forcing from environmental variability and climate change. This increased understanding and reduction of uncertainties in proxy measurements significantly contributes to OA research. In addition, PACE, SBG, and GLIMR will extend key Earth system data records on global ocean ecology and biogeochemistry.

NASA carried out the Biodiversity Field Campaign in the Greater Cape Floristic Region of South Africa, which included aquatic components. Part of the work conducted within the framework of the biodiversity assessment included measurements of ocean chemistry, including dissolved inorganic carbon (DIC) and alkalinity, and aquatic ecosystem assessments.

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 DIC, total alkalinity (TA), and pH throughout the full water column in open-ocean waters. NOAA and NSF also funded new collection activities of environmental DNA (eDNA) on GO-SHIP cruises. NASA funded the collection of select particle and pigment bio-optical parameters on GO-SHIP cruises, which will continue through 2028 to assess data quality from NASA’s most recent ocean satellite PACE. The GO-SHIP 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.

NOAA maintained 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, Chesapeake Bay), and U.S. coral reef ecosystems (e.g., Puerto Rico, Florida, Hawai'i, American Samoa, Flower Garden Banks, Gray's Reef). In addition, NOAA maintained 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 ships of opportunity effort for surface CO_2 observations in the world, collecting underway partial pressure of carbon dioxide (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.

NSF also supports mid-ocean time series stations in both the Atlantic and Pacific Oceans, the Bermuda Atlantic Time-series Study and the Hawai'i Ocean Time-series. Observations at these sites included measurements of ocean primary productivity and changes in ocean biology, nutrients, pH, and carbonate chemistry. 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 in the North Atlantic Ocean.

NSF continued funding the Global Ocean Biogeochemistry Array to deploy profiling floats equipped with pH; oxygen; nitrate; conductivity, temperature, and depth; and optical sensors to contribute to the international Biogeochemical Argo program.

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

NASA supported the development of models to examine the linkages between atmospheric composition, OA, and biological productivity in the Southern Ocean, including how they relate to the interannual variability in sea ice presence and concentration.

NASA supported modeling efforts focused on improving the characterization of carbon transfer from the land to the ocean, including the effects of land use and changes on the resulting global ocean carbon flux and impacts to coastal zones, including acidification.

Through the NOPP, a project was funded to conduct multiscale observing system simulation experiments for iron fertilization in the Southern Ocean, Equatorial Pacific, and Northeast Pacific; models will examine the extent of carbon sequestration and potential effects on ecosystems.

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

Following Honeywell's announcement that they would discontinue production of the ion-sensitive field-effect transistor chips common to the most widely used pH sensors, NSF funded a project to develop new pH sensors deployable on a variety of ocean sensing platforms.

NIST worked to develop capabilities to provide traceable measurements for the CO_2 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'Essais (LNE) and others to establish the Seawater pH Task Group within the Consultative Committee for Metrology in Chemistry and Biology at the International Bureau of Weights and Measures. NIST and LNE coordinated a pilot interlaboratory study 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 CO_2 reference material program, the sole source of ocean carbon reference materials, 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 to create a global multi-distribution center model for ocean carbon reference materials.

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

Agencies who participate in the IWG-OA, including Department of State, EPA, Fish and Wildlife Service , NASA, NOAA, NPS, NSF, USDA, and USGS continued to support the United States Coral Reef Task Force, a group established in 1998 by a Presidential Executive Order to lead U.S. efforts to preserve and protect coral reef ecosystems. The Task Force has additional members from federal agencies, U.S. States, Territories, Commonwealths, Freely Associated States, and Fishery Management Councils.

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

The Global Ocean Acidification Observing Network (GOA-ON) is a collaborative international network that aims to detect and understand the drivers of OA, the resulting impacts on marine ecosystems, and to make the information available to optimize modeling studies. GOA-ON is a key international organization that NOAA utilizes to engage in OA research and monitoring globally. GOA-ON fosters collaboration through ten regional hubs and facilitates submission of OA data in support of Sustainable Development Goal 14.3.1 Indicator, which calls for the average pH measured at an agreed suite of representative sampling stations. NOAA continued funding one of two co-chairs for the GOA-ON and the operation of the GOA-ON data portal. NOAA also provided one secretariat member for GOA-ON and participated in the North American Hub. In 2023, GOA-ON hosted the third virtual OA week, an online virtual webinar series for the international community. NOAA also continued to engage in the GOA-ON UN Ocean Decade Program, Ocean Acidification Research for Sustainability.

In 2022, NOAA organized the 5th International Symposium on the Ocean in a High CO_2 World in partnership with the International Atomic Energy Agency and the Pedro Ruiz Gallo National University in Lima, Peru. The conference brought together participants from across the globe to discuss OA, its impacts on the marine environment, and approaches for mitigation, forecasting, modeling, and experimentation.

NOAA continued to fund scholarships for the Pier2Peer Program, a GOA-ON mentorship program that matches senior researchers with early career scientists to exchange expertise and support international collaborations.

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

Theme 7: Data Management, Integration, and Synthesis

Surface CO_2 measurements collected by NOAA and NSF from GO-SHIP, moorings, and ships of opportunity are collated in the SOCAT. The 2022 version of SOCAT contained 33.7 million observations of surface ocean fCO_2 (fugacity of 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 supported the global 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, including the GO-SHIP, ships of opportunity, and moorings. 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

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, as further 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.

NOAA continued to fund a comprehensive research portfolio focused on understanding the impacts of OA on marine species, primarily executed by NOAA's fishery science centers across the country. NOAA also funded a suite of projects in collaboration with Fisheries and Oceans (DFO) Canada. The NOAA-DFO projects aimed to advance joint activities related to OA monitoring, research, experimentation, and modeling on species response to OA, with a focus on supporting early career researchers and international collaboration.

USDA continued to fund the Interagency Working Group for Farming Seaweeds and Seagrasses, which is responsible for reporting on opportunities for farming seaweeds and seagrasses to deacidify ocean environments and provide agricultural products. The working group continued to hold stakeholder listening sessions and funded six pilot projects.

USGS continued regional-scale assessments of seafloor erosion rates in coral reef ecosystems of the Atlantic Ocean, Pacific Ocean, and Caribbean Sea, and integrated process studies to identify and quantify multi-stressor factors contributing to reef ecosystem degradation, support coastal hazards risk assessments, and habitat restoration planning and implementation. USGS maintains an extensive repository of coral and sediment cores and performs ongoing analytical projects to recover and interpret historical records of environmental change in coastal environments.

Theme 2: Monitoring of Ocean Chemistry and Biological Impacts

Some 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. 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 initiated the incorporation of a coastal acidification pilot indicator into the 2020 National Coastal Condition Assessment Survey. Data from the 899 estuarine sites from the 2020 survey were finalized and are being used to model TA in estuaries. EPA submitted a proposal to continue this research indicator for the 2025 National Coastal Condition Assessment survey and began evaluating pH sensors for the 2025 survey.

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. They will also characterize the relative vulnerabilities of U.S. estuaries to further acidification from land-based and atmospheric CO_2 sources.

NOAA funded a project to equip a fleet of next-generation autonomous underwater gliders with novel pH sensors to estimate surface pCO_2 and demonstrate the ability of the fleet to measure CO_2 uptake in the Gulf Stream along the East Coast and across all seasons.

NOAA conducts regional, hydrographic, coastal cruises that cover the U.S. regions on an approximately 4-year cycle. In 2022, the third East Coast Ocean Acidification Cruise collected high quality data for monitoring the carbon system along the U.S. East Coast, from Maine to Florida.

NOAA and NASA provided funding through NOAA to assess marine ecosystem health and the influence of changing ocean dynamics on plankton through biological measurements on U.S. GO-SHIP cruises.

NOAA continued the National Coral Reef Monitoring Program (NCRMP), which is the world's largest monitoring program designed to support the conservation of coral reef ecosystems. NCRMP provides consistent, sustained, and long-term measurement of key indicators that gauge the status and trends of U.S. coral reef health in the Caribbean, Southeast and Gulf of Mexico, and the Pacific Islands. NCRMP collects both carbonate chemistry data and biological data to assess impacts of climate change and OA.

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

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

NOAA funded research to improve data assimilation systems for faster execution, higher resolution, and application coupling for U.S. West and East coast ocean forecast systems.

NOAA funded a project to identify areas subject to the extremes of OA and compound stressors (e.g., warming, nutrient availability, and deoxygenation) using a fully-coupled earth system model run under a range of climate change and mitigation scenarios.

NOAA funded the analysis of historical and future projections of OA from the NOAA Coupled Carbon-Chemistry-Climate Earth System model contributing to the Coupled Model Intercomparison Project's sixth (CMIP6) phase and development of the next generation version for its seventh phase.

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. These guidelines target various audiences with differing areas of expertise, from shellfish growers to citizen monitoring groups and advanced chemistry laboratories. EPA also tested two types of technology for low-cost portable and handheld pH instruments to be used by citizen scientists and educators.

NOAA continued funding development of a pCO_2-DIC sensor to improve data return of two carbon parameters from NOAA OA buoys. NOAA also tested prototype TA sensors at coral reef test-beds.

NOAA funded the development and testing of a standard operating procedure for the production of limited quantities of secondary carbon-in-seawater reference materials.

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

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 postgraduate students.

NOAA supports the NOAA OA Program (OAP) as directed by the Federal Ocean Acidification Research and Monitoring (FOARAM) Act of 2009. The OAP coordinates OA-related research and monitoring across NOAA and directly supports OA efforts in NOAA laboratories. The OAP 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. The OAP also conducts education, outreach, and engagement on OA domestically and internationally. The OAP also coordinates a NOAA Ocean Acidification Working Group to build coordination among labs and programs across the agency.

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 funding the Ocean Acidification Information Exchange (OAIE), 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. USGS also engages as a steering committee member for the OAIE.

NOAA continued to fund and support six coastal acidification networks (CANs) in the Northeast, Mid-Atlantic, Southeast, Gulf of Mexico, Alaska, and the California Current. The CANs are grassroot capacity building organizations that play a critical role in supporting regional monitoring, community engagement, and sharing of information related to OA adaptation and mitigation. The CANs bring together researchers, industry, state agencies, educators, and others to leverage expertise and collectively address OA at a regional level. Other agencies actively engage with CANs, including EPA and USGS.

In 2023, the NOAA OAP hosted a community meeting to foster collaborations within the OA research community, identify critical research gaps, and shape future strategies for addressing OA.

NOAA continued supporting development of educational tools related to OA through the OA Education Mini Grant Program. Projects funded in 2022 included developing of K-12 teaching modules, online toolkits, and workshops that focus on culturally relevant approaches to OA education; building partnerships with non-coastal schools to increase capacity for OA education; developing virtual high school classroom OA toolkits; conducting a professional development program for middle school teachers to address gaps in OA education; and developing a game-based curriculum about OA and actions we can take to help.

NOAA provided financial support to the U.S. Carbon Cycle Science Program Office, which serves as the authoritative information source for U.S. carbon cycle research, observing, and modeling communities through cross-sector engagement and provides information for decision makers across levels of government.

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

NSF also supported a 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.

Theme 7: Data Management, Integration, and Synthesis

BOEM funded Argonne National Laboratory to summarize impacts of GHG emissions on coastal and marine environments, including ocean and coastal acidification. The work will highlight possible mitigation opportunities to reduce GHG emissions from offshore facilities, and discuss different approaches that EPA, the Bureau of Land Management, and the Pipelines and Hazardous Materials Safety Administration are using to reduce GHG emissions from oil and gas sources.

NOAA supported public access and archiving of OA and carbon data through OCADS. NOAA continued developing the Science Data Information System, which supports data submission and metadata assembly for OCADS.

NOAA and NSF also supported the Climate and Ocean: Variability, Predictability and Change (CLIVAR) and Carbon Hydrographic Data Office which supports oceanographic research by providing access to vessel-based conductivity, temperature, and depth and hydrographic data from GO-SHIP, the world ocean circulation experiment, CLIVAR, and other repeat hydrography programs.

NOAA funded a project to develop a new OA data product to track temporal changes of major OA indicators, including pH, aragonite saturation state, and Revelle factor, in the U.S. large marine ecosystems; the results will be integrated into the National Marine Ecosystem Status website.

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.

Northeast

This region includes Maine, New Hampshire, Massachusetts, Rhode Island, and Connecticut.

Theme 1: Research to Understand Responses to Ocean Acidification

The EPA continued its work on biological responses to OA and developed a laboratory 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. EPA also studied the combined effects of acidification and nutrient enrichment on interactions between molluscan grazers and their macroalgae food resources.[1] In 2022, EPA began a new collaboration with the University of Rhode Island on the response of fixed-station pH and dissolved oxygen time series in Narragansett Bay to nutrient loading reductions.

NOAA continued funding research on species response to OA at the Northeast Fisheries Science Center (NEFSC). Researchers conducted long-term multiple generation experiments with scallops to estimate their robustness and adaptive potential to OA. Research on Atlantic surfclams included conducting field studies to measure carbonate chemistry in surfclam habitats, validating a dynamic energy budget model using field data, and determining the plasticity of two subspecies.

NOAA funded research to assess OA as a driver for enhanced metal uptake by blue mussels; this work included laboratory and field components.

NOAA funded several research projects in the Northeast focused on harmful algal blooms (HABs) and OA. The first project is investigating how three prominent HABs on the East Coast respond to OA, how they may be impacted by future OA scenarios, and how the co-occurrence of OA and these HABs may impact valuable bivalves and fish. Another project is evaluating whether HAB species may have a competitive advantage over other phytoplankton in response to OA.

[1] Ober, G. T., Thornber, C. S., & Grear, J. S. (2022). Ocean acidification but not nutrient enrichment reduces grazing and alters diet preference in Littorina littorea. *Marine Biology*, *169*(9), 112.

NOAA funded two collaborative NOAA-DFO projects in the Northeast related to OA biological research. The first will develop a method for characterizing dissolution of sea scallop shells and apply this methodology to shells from the NOAA NEFSC scallop survey to determine if OA impacts are observed in the field. A second project will support a laboratory exchange of early career scientists to develop consistent research methodologies for studying OA effects of bivalves.

NOAA funded two OA research projects in the Northeast through state Sea Grant programs. A project was funded through New York Sea Grant to study the spatial variability of carbon storage in eelgrass sediments across the Long Island south shore and Peconic estuaries. A project funded through Connecticut Sea Grant will study the effects of OA and warming on population fitness of copepods and if there are costs to adaptation.

NOAA funded a project to study the impacts of OA and warming on Atlantic surfclams and provide existing farmers and the surfclam fishing sector with commercially relevant data for use in farm-scale business planning.

NSF funded a project to study drivers of OA and the impacts of nutrient loading reductions in Narragansett Bay, using observations and models.

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.[2] 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.

NASA continued to support 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, and they include the generation of specific products related to particulate inorganic carbon.

NOAA funded the procurement of a Channelized Optical System II, a prototype in situ sensor that can continually measure DIC and either pH or pCO_2, to integrate into NEFSC field surveys.

NOAA funded a collaborative NOAA-DFO project to measure carbon remineralization rates in sediments and fluxes of DIC, TA, and nutrients to the overlaying water along the Labrador Shelf to the Scotian Shelf.

NOAA continued funding an OA mooring in the Gulf of Maine; repairs were also supported after the buoy suffered a ship strike in 2022. NOAA continued collecting underway OA measurements on the fisheries ship *Henry Bigelow*.

NOAA continued funding OA monitoring on seasonal NEFSC Ecosystems Monitoring (EcoMon) cruises, which cover the Gulf of Maine to North Carolina. This team is also developing a biological indicator to OA and creating a new OA synthesis product to be used in the NEFSC's State of the Ecosystem Report.

[2] Pimenta, A. R., Oczkowski, A., McKinney, R., & Grear, J. (2023). Geographical and seasonal patterns in the carbonate chemistry of Narragansett Bay, RI. *Regional Studies in Marine Science*, *62*, 102903.

NOAA funded a project through Woods Hole Oceanographic Institution's (WHOI's) Sea Grant to continue collecting water quality data near Cape Cod and Duxbury Bay and to collaborate with shellfish farmers and other local monitoring groups to collect OA data in areas of potential vulnerability.

The Pioneer Array, an element of NSF's OOI, continued to operate and collect OA relevant data through November 2022 in the Northeast between central New Jersey and Martha's Vineyard, Massachusetts. Data collection was then suspended to prepare for the array's move to the southern Mid-Atlantic Bight in 2024.

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

The EPA conducted research to evaluate responses of estuarine production and carbonate chemistry to nutrient loading using stable carbon isotopes.

NOAA funded a project through Massachusetts Institute of Technology (MIT) Sea Grant to develop a regional OA model for the Northeast Coast using big data and machine learning.

Theme 4: Technology Development and Standardization of Methods

The EPA continued investigating low-cost alternatives for handling and analysis of seawater OA samples. EPA also tested two types of technology for low cost portable and handheld pH instruments to be used by citizen scientists and educators.

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

NOAA continued funding a regional vulnerability assessment that is assessing the vulnerability of the Atlantic sea scallop fishery using regional projections of OA and temperature, and then developing management recommendations to assist the industry in adapting to projected changes.

NOAA funded a collaborative NOAA-DFO project to synthesize data on the effects of elevated CO_2 on transboundary marine taxa in the Northwest Atlantic.

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 (NECAN) is a joint federal, academic, and industry partnership established under the Northeast Regional Association of Coastal and Ocean Observing Systems; it is funded by NOAA and EPA also participates as a member. NECAN led the synthesis and dissemination of regional ocean and coastal acidification data and information from the Long Island Sound to the Scotian Shelf through workshops, web development, and other efforts. NECAN also 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. The organization also coordinates and develops regional priorities for science observing and research investments designed to further understanding of OA. To aid in the development of a regional OA monitoring plan, NECAN hosted a series of webinars during the Spring and Summer of 2023. These webinars were focused on better understanding the status and trends of acidification in the coastal waters of the Northeastern United States. These webinars covered a wide range of topics, including policy needs, new technology, and biological impacts.

NOAA funded a stakeholder engagement project through MIT Sea Grant focused on improving water quality and shellfish monitoring efforts. This contributed to better mitigation and adaptation strategies to warming and OA.

Mid-Atlantic

This region includes New York, New Jersey, Delaware, Maryland, and Virginia.

Theme 1: Research to Understand Responses to Ocean Acidification

NSF funded a collaborative research project to study how larger organisms, such as oysters, clams, salt marshes, mangroves, and seagrasses, are influencing estuarine carbon and alkalinity dynamics. The project included coordinated field measurements in tidal tributaries of the Chesapeake Bay, laboratory experiments, historical data analysis, and numerical modeling.

Theme 2: Monitoring of Ocean Chemistry and Biological Impacts

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.

NOAA continued funding an OA mooring in the Chesapeake Bay.

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

NOAA continued funding the Mid-Atlantic Coastal 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. Both NOAA and EPA participated as federal representatives. MACAN works to develop a better understanding of the processes associated with estuarine, coastal, and ocean acidification; predict the consequences for marine resources; and devise local adaptation strategies that enable communities and industries to better prepare and adapt.

Southeast and Gulf of Mexico

This region includes North Carolina, South Carolina, Georgia, Florida, Alabama, Mississippi, Louisiana, and Texas.

Theme 1: Research to Understand Responses to Ocean Acidification

NOAA funded the analysis of eDNA collected on the 2021 Gulf of Mexico Ecosystems and Carbon Cruise to develop models of ecosystem diversity, develop indicator taxa of OA in the Gulf Coast, and predictive models of HABs and OA.

NOAA funded research to characterize and forecast coastal ecosystem responses to multiple stressors, including OA, hypoxia, HABs, warming, and eutrophication, for management and restoration applications in South Florida.

NOAA invested in new instruments needed to continue OA research at the Atlantic Oceanographic and Meteorological Laboratory; these included a new micro computed-tomography machine and new pH sensors.

NOAA funded a project through Georgia Sea Grant to study the relationship between oyster density and pH and dissolved oxygen in aquaculture to make recommendations to growers.

Through the NOPP, a project was funded to explore the carbon capture capacity and OA mitigation potential of seaweed farms in Florida and Japan.

NSF funded a rapid response project to study impacts of Hurricane Ian on carbon and nutrient cycling along a gradient from estuaries to shelf waters on the west Florida shelf; this will inform a model to predict the impact of future hurricanes on OA and other stressors.

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 to understand the potential for habitat restoration there to mitigate acidification's 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 is also currently investigating interactions between coastal acidification, HABs, and toxin production in Tampa Bay, Florida.

Theme 2: Monitoring of Ocean Chemistry and Biological Impacts

BOEM and NOAA continued a project intended to collect OA monitoring data at the Flower Garden Banks National Marine Sanctuary. The project collected preliminary chemical and biological monitoring data 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. Unfortunately, the buoy was destroyed by a hurricane, and only limited data was collected for analysis.

Coastal acidification in situ monitoring continued at EPA's National Estuary Program sites in Tampa Bay Estuary Program (Florida) using pH and pCO_2 autonomous sensors. This monitoring 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.

NASA supported research in southern Florida focused on carbon fluxes from coastal ecosystems by combining remote-sensing products from aircraft and satellites, and ground observations.

NOAA funded analysis of biological samples collected during the 2021 Gulf of Mexico Ecosystems and Carbon Cruise to evaluate the impact of OA on plankton, HABs, and fish distribution.

NOAA invested in multiple efforts to monitor OA in estuarine and coastal regions. This included adding carbonate chemistry monitoring to HABs monitoring cruises conducted on the Western Florida Shelf, continuing a collaboration with select NPS sites in the Gulf of Mexico and East Coast to collect near-shore data, and complementing underway surface pCO_2 measurements with underway TA measurements in the Gulf of Mexico and East Coast.

NOAA continued funding OA moorings in Gray's Reef National Marine Sanctuary in Georgia and off of coastal Louisiana in the northern Gulf of Mexico.

NOAA continued collecting underway OA measurements on the fisheries ship *Gordon Gunter*.

NOAA funded a project through South Carolina Sea Grant to provide a first characterization of OA in Long Bay, South Carolina.

NOAA continued monitoring OA at Atlantic U.S. coral reefs through NCRMP. NCRMP monitoring in the region consisted of a high-resolution time series of carbonate chemistry and biweekly water sampling collected at the Cheeca Rocks buoy in Florida, diel carbonate chemistry sampling at fixed sites, and discrete carbonate chemistry sampling at random sites. Sampling in 2022 occurred at Flower Garden Banks and Florida sites.

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

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

EPA continued field assessment of acidification and water quality conditions in Pensacola Bay in support of biogeochemical model development addressing estuarine and coastal acidification. EPA is utilizing its newly publicly released Coastal Generalized Ecosystem Model (CGEM) to implement a more comprehensive modeling approach aimed at climate change and acidification impacts, including simulation of the full carbonate system and sediment diagenesis. In support of this effort, EPA published one manuscript describing hydrodynamic model predictions of climate change effects in Pensacola Bay,[3] and EPA will publish an additional manuscript describing the CGEM model soon.[4]

NOAA funded a project to use high-resolution ocean-biogeochemical models to reproduce historical OA patterns on the East and Gulf coasts, project future OA trends, and advance understanding of river runoff and regional circulation patterns as drivers of carbon system variability.

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

NOAA continued to fund two regional CANs, the Southeast Ocean and Coastal Acidification Network (SOCAN) and the Gulf of Mexico Coastal Acidification Network (GCAN). 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 both SOCAN and GCAN and is committed to developing more effective methods and partnerships to deliver science to policy and decision-makers effectively.

[3] Duvall, M.S., Jarvis, B.M., Wan, Y. (2022). Impacts of Climate Change on Estuarine Stratification and Implications for Hypoxia Within a Shallow Subtropical System. Estuarine Coastal and Shelf Science. 279 (1). https://doi.org/ 10.1016/j.ecss.2022.108146

[4] Jarvis, B.M., Lehrter, J.C., Lowe, L., Penta, B., Wan, Y., Duvall, M., Melendez, W., Simmons, C., Ko, D.S. (2024). CGEM 1.0: Flexible Model Formulations for Simulating Complex Biogeochemical Processes in Aquatic Ecosystems. In revision with Ecological Modelling.

Caribbean

This section covers activities funded in the U.S. jurisdictions in the Caribbean, Puerto Rico and the U.S. Virgin Islands.

Theme 1: Research to Understand Responses to Ocean Acidification

NSF funded a new, five-year study of how the presence of dead coral in a reef ecosystem contributes to the resilience of the ecosystem to further disturbances.

Theme 2: Monitoring of Ocean Chemistry and Biological Impacts

NASA, through its Minority University Research & Education Program, supported research in Puerto Rico and the U.S. Virgin Islands aimed at further understanding the impact of Sargassum inundation events on coastal water chemistry and ecosystems, including coral reefs.

NOAA continued monitoring OA at Atlantic U.S. coral reefs through NCRMP. NCRMP monitoring in the region consisted of a high-resolution time series of carbonate chemistry and biweekly water sampling collected at the La Parguera buoy in Puerto Rico, diel carbonate chemistry sampling at fixed sites, and discrete carbonate chemistry sampling at random sites. Sampling in 2022-2023 took place in both Puerto Rico and the U.S. Virgin Islands.

NOAA funded collection of underway OA measurements in the Caribbean on the *Equinox* and *Allure of the Seas*.

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

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

West Coast

The West Coast region includes the states of Washington, Oregon, and California.

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; they included carbonate chemistry as one of the response metrics.[5] These mesocosm experiments elucidate the role of seagrass and macroalgae in moderating acidification.

NOAA continued funding research on species response to OA at the Northwest Fisheries Science Center (NWFSC) and Southwest Fisheries Science Center (SWFSC) laboratories. Research on

[5] Kaldy JE, Brown CA, Pacella SR. 2022. Carbon limitation in response to nutrient loading in an eelgrass mesocosm: influence of water residence time. *Marine Ecology Progress Series*. 689: 1-17. https://doi.org/10.3354/meps14061

fish included work to study mechanisms underlying sablefish behavioral resilience to OA and the potential effects of OA on pink and Chinook salmon behavior and physiology. Research on Dungeness crab included studying the sensitivity of different populations to OA, studying the calcification and dissolution processes, and studying which aspect of the carbonate chemistry system drives increased mortality in high CO_2 conditions. Research on krill continued to conduct linked multi-stressor experiments and modeling to study how OA and warming may influence development and population dynamics. Additional research focused on conducting experiments on the effects of warming, OA, and deoxygenation on krill; developing models that link results to changes in populations; and using results to analyze variability in observational time series of krill.

NOAA also funded prototype development of a novel multi-stressor experimental system for OA research to be used by the NWFSC.

NOAA funded a collaborative NOAA-DFO project to estimate the lifetime exposure of pteropods to OA using a particle tracking tool paired with a circulation model.

NOAA funded researchers and shellfish growers to collaborate to integrate oceanographic measurements, field work, and laboratory experiments to examine the physiological tolerance and survival of diploid and triploid oysters under multiple stressors (e.g., OA, temperature, and dissolved oxygen).

NOAA funded a number of OA research studies through state Sea Grant Programs. The following four projects were funded through California Sea Grant. First, a project will study how copper rockfish offspring respond to OA and hypoxia based on the environmental conditions their parents experienced; both lab experiments and field study results will be incorporated into a stock assessment model. Next, a project team will build a California OA and hypoxia portal to enable synthesis and understanding of state-wide status and trends. Funding is also supporting a project to study how OA affects gene expression in Pacific littleneck clams and evaluate the use of Indigenous shellfish management techniques in mitigating against OA and promoting healthy populations in northern California. Lastly, a research team will work to improve monitoring of OA in Humboldt Bay, investigate the potential role of eelgrass in reducing OA, and establish baseline monitoring of eelgrass. Two projects were funded through Washington Sea Grant; one to use genomic science to identify alternatives to triploid Pacific oysters for the shellfish industry that are resilient to acidification, and one to form a collaborative hub in partnership with Oregon and California Sea Grant to promote sustainable aquaculture on the West Coast.

NOAA funded a project to study the response of HABs to OA, warming, and nutrients in the Salish Sea.

NOAA funded a project examining the effects of low dissolved oxygen and pH on the survival, growth, and metabolism of endangered white abalone.

Through NOPP, a project was funded to study the potential of ocean alkalinity enhancement (OAE) to mitigate global CO_2-driven climate change and regional impacts of OA by implementing OAE technology in a field trial in the Pacific Northwest and modeling and monitoring the OAE and regional chemical impacts.

The NPS Center for Ocean Acidification Monitoring (CFOAM) at Olympic National Park coordinated and conducted continuous OA monitoring (including pH, salinity, temperature, TA, dissolved oxygen), in the intertidal zone. Monitoring took place at Olympic National Park, San Juan Island National Historical Park, Channel Islands National Park, Cabrillo National Monument, and Navy-owned San Clemente Island. Instrument packages are maintained by and shipped from the NPS CFOAM lab to sites on a periodic basis. Site staff swap out old instrument packages

with new packages and take water samples that are then shipped back to the CFOAM lab for analysis, data management, and equipment maintenance.

In 2022, NPS CFOAM collaborated with NOAA and other scientists to conduct a regional vulnerability assessment for OA on the Olympic coast that has been designated by NOAA as an OA Sentinel Site. Data from CFOAM monitoring was used in an analysis with offshore OA monitoring efforts coordinated by NOAA to assess the current and future impacts of OA on key organisms, particularly those vital to Native American tribes on the Olympic coast.

NSF continued supporting a project examining ecosystem metabolism in rocky intertidal communities of southern California under warming and acidifying conditions. NSF funded a new project to examine how OA and nutrient pollution affect growth and survival of eelgrass in two urbanized California estuaries.

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, researchers examined how watershed activities interact with natural events to exacerbate the magnitude and duration of coastal acidification and hypoxia in these estuarine habitats.

NOAA continued funding the underway OA monitoring system on the NOAA ship *Bell M. Shimada*, which operates on the West Coast.

NOAA continued funding four OA moorings on the West Coast. Two are located in Southern California (one open ocean and one in the coastal ocean), one is offshore of southern Oregon, and one is off the outer coast of Washington near La Push within the Olympic Coast National Marine Sanctuary.

Additionally, NOAA funded OA measurements in the Pacific Northwest from one buoy in the Columbia River and six buoys in Puget sound. In California, NOAA funded OA measurements at a number of automated shore stations, including in Morro Bay, San Luis Bay, Monterey, Moss Landing, San Francisco Bay, Bodega Bay, Humboldt Bay, and Trinidad. NOAA also supported a self-calibrating SeapHOx sensor for pH and dissolved measurements at Scripps Pier in Southern California.

NOAA funded a project to collect carbonate chemistry samples in partnership with the California Cooperative Oceanic Fisheries Investigation (CalCOFI), which has monitored physical and biological components of the Southern California Current Ecosystem since 1951.

NOAA provided funding to support operations and maintenance for California's underwater glider network, which measures pH among other variables.

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 project through California Sea Grant to use global climate projections to characterize the progression of OA and hypoxia in the California Current and develop an interactive web tool tailored towards management.

NOAA continued to develop and operate the Joint Institute for the Study of the Atmosphere and the Ocean's (JISAO's) Seasonal Coastal Ocean Prediction of the Ecosystem to provide seasonal predictions of OA.

Theme 4: Technology Development and Standardization of Methods

NOAA funded a project to integrate pH and nitrate sensors onto the newly developed Spray2 underwater glider.

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

NOAA continued funding 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 engaging shellfish growers and regulators to identify challenges in implementing mitigation strategies.

NOAA funded a project to advance research on the impacts of multi-stressors (e.g., OA, hypoxia, marine heatwaves, and HABs) using observations, modeling, and experiments to inform management in the Northern California Current.

NOAA continued funding a regional vulnerability assessment to assess the vulnerability of coastal communities in California and Oregon to OA and how they adapt. The project will also evaluate the barriers preventing communities from coping to inform policy.

NOAA funded the development of a decision tool for sea farmers to balance tradeoffs between growing diploid and triploid Pacific Oysters. This tool considers environmental drivers including temperature, pH, and oxygen.

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. EPA and NOAA participated in Oregon Department of Environmental Quality's Ocean Acidification and Hypoxia Technical Workgroup. The objective of the OAH technical workgroup was to synthesize evidence that could support policy decisions on determining OAH impairment within Oregon's territorial waters.

NOAA continued to fund the California Current Acidification Network, a collaboration of interdisciplinary scientists, resource managers, industry members, and representatives from local, state, and Tribal governments working to strengthen resilience and adaptive capacity to OA.

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. The first biennial OASeS symposium was held in 2022.

NOAA supported an OA liaison position at Washington Sea Grant to strengthen core NOAA research and outreach functions and deliver OA information to key audiences through outreach and education.

Theme 7: Data Management, Integration, and Synthesis

NOAA provided funding through the Central and Northern California Ocean Observing System to provide OA data management support for the CalCOFI, Applied California Current Ecosystems Studies, and Trinidad survey programs, the Monterey Bay Aquarium Research Institute moorings, and marine protected area monitoring programs. NOAA also provided funding to the Northwest Association of Networked Ocean Observing Systems to support data management of their OA data.

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 was funded to study the interaction between OA and other stressors, including temperature and nutrients, on the behavior of king crabs and the physiological sensitivity of snow crab and Tanner crab. For groundfish, research was funded to study the interactions of OA and temperature on the early life stages of Pacific cod, yellowfin sole, and Arctic cod. Additionally, next-generation sequencing techniques were used to assess adaptive capacity and understand mechanisms underlying the effects of OA on Alaskan crab and fish species.

NSF provided continuing support for a project researching ecosystem impacts of OA and other stressors on kelp forests in southeast Alaska.

Theme 2: Monitoring of Ocean Chemistry and Biological Impacts

NASA supported research focused on better characterizing the fluxes of organic carbon from boreal environments to the Arctic Ocean utilizing satellite remote-sensing and ground observations to improve the understanding of coastal biogeochemistry. This work includes collaboration with Indigenous communities.

NASA's investments also include research on the spatio-temporal patterns of air-sea interactions in the Pacific and Atlantic sectors of the Arctic Ocean with the goal to produce long-term, high-resolution flux maps and understand the underlying mechanisms that drive the spatial heterogeneity and long-term variability.

NOAA continued funding the underway OA monitoring system on the NOAA ship *Oscar Dyson*, which operates in Alaskan waters. NOAA also supported underway OA sampling on the MV Columbia Ferry, which is a part of the Alaska Marine Highway System. Additionally, operation of two OA moorings continued, one in the northern Gulf of Alaska and one in the southeastern Bering Sea.

NOAA supported analysis of OA sampling conducted along the Seward Line in the Gulf of Alaska.

NOAA sampled carbonate chemistry in Alaskan waters in partnership with the Alaska Fisheries Science Center's annual population survey program. In 2023, pH data were also collected on the Eastern Bering Sea bottom trawl survey.

NOAA continued to fund a community sampling program, which includes operation of Burke-O-Lators with three Tribal organizations in Seward, Kodiak, and Sitka.

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

NOAA expanded the model hindcast of a model developed for seasonal forecasts of OA in the Bering Sea, conducted retroactive reforecasts, and new model forecasts. Forecasts are included as part of an OA index in the annual ecosystem status report for Alaska.

NOAA continued funding the development of a bioeconomic model to forecast effects of OA on Eastern Bering Sea crab, northern rock sole, and Alaska cod fisheries.

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

NOAA continued funding a regional vulnerability assessment to understand OA threats to traditional and coastal Alaska industries in south-central and southeast Alaska; the project is developing decision support tools to incorporate OA into localized socio-ecological systems.

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

NOAA continued to fund the Alaska OA Network (AOAN), which engages with scientists and stakeholders to expand the understanding of OA processes and consequences, as well as potential adaptation strategies. AOAN convenes OA researchers, works with the fishing and crab industry to share information, supports Tribal community sampling coordination, and conducts outreach to diverse audiences, including policy makers and coastal communities. NOAA also funded AOAN to provide additional trainings and workshops for Tribal community samplers.

NOAA funded a 2023 Alaska Sea Grant State Fellow to build tribal capacity for climate change adaptation, which included engaging with tribes on OA monitoring.

Theme 7: Data Management, Integration, and Synthesis

NOAA provided funding to the Alaska Ocean Observing System to support data management services for OA data.

Great Lakes

The Great Lakes region includes Lake Superior, Michigan, Huron, Erie, and Ontario.

Theme 1: Research to Understand Responses to Ocean Acidification

NOAA funded research to study the synergistic impact of climate-induced OA, temperature, TA, and nutrients on cyanobacteria HABs in the Great Lakes.

Theme 2: Monitoring of Ocean Chemistry and Biological Impacts

NOAA funded the establishment of a long-term monitoring program through the Great Lakes Environmental Research Laboratory to collect pCO_2 and TA at stations in Thunder Bay National Marine Sanctuary.

NOAA supported a pCO_2 system on the Lake Express, a ferry on Lake Michigan, to collect data along the transect between Muskegon, Michigan and Milwaukee, Wisconsin several times a day.

Pacific Islands

This section discusses activities funded in U.S. jurisdictions in the Pacific Islands, including the State of Hawai‘i, the Territories of American Samoa and Guam, the Commonwealth of the Northern Marianas Islands, and the U.S. Pacific Remote Island Areas.

Theme 1: Research to Understand Responses to Ocean Acidification

NOAA funded a project through Hawai‘i Sea Grant to develop a feasible model for near-shore integrated multitrophic aquaculture to test the use of bivalves and macroalgae for water quality improvement and OA mitigation.

NSF provided continuing support for a project examining the susceptibility of deep-sea corals to OA in the Northwestern Hawaiian Islands and Emperor Seamount Chain. NSF funding also continued for a project studying the influence of environmental pH variability and thermal sensitivity on the resilience of reef-building corals in Hawai‘i to OA stress. NSF funded a new project to improve methods for coral skeletal analysis, a technique used to study OA and warming, and to build a virtual coral core repository.

Theme 2: Monitoring of Ocean Chemistry and Biological Impacts

NOAA continued funding the collection of underway pH and oxygen data on equatorial Pacific M/V *Bluefin* cruises that service the Pacific Marine Environmental Laboratory moored CO_2 and OA sensor network.

NOAA continued monitoring OA at Pacific U.S. coral reefs through NCRMP. NCRMP monitoring in the region consisted of diel carbonate chemistry sampling at fixed sites and discrete carbonate chemistry sampling at random sites. NCRMP also conducted OA ecological response monitoring, which included coral growth and calcification rates, net carbonate accretion, and bioerosion rates. Field missions in 2022-2023 took place in American Samoa, the Pacific Remote Islands Areas, and the Main and Northwestern Hawaiian Islands.

NOAA continued funding an OA buoy in Fagatele Bay in American Samoa. The National Marine Sanctuary of American Samoa also continued long term ecological monitoring that is leveraged to assess OA impacts. In Hawai‘i, operation continued of two OA buoys in Kaneohe Bay on the eastern side of Oahu.

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

NOAA funded a postgraduate E. Gordon Grau Coastal and Marine Resource Management and Policy Fellow to focus on OA in Hawai‘i. NOAA also funded a Ph.D student to receive the Dr. Nancy Foster Scholarship in order to study the impact of OA on deep sea corals in the North Pacific.

Arctic

Theme 1: Research to Understand Responses to Ocean Acidification

NOAA funded a collaborative NOAA-DFO project to study the effects of OA on Arctic cod reproductive success.

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 has an additional mooring near the Boulder Patch Area of Special Biological Concern in the Beaufort Sea. This sensor detects seawater pH variation in relation to freshwater run-off. Data from these Arctic moorings facilitates a better understanding of oceanic uptake of CO_2 in the Arctic and potential effects related to offshore oil and gas activities.

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

NOAA funded a collaborative NOAA-DFO project to improve model parametrizations of the coupled ice-ocean carbon system and compare model outputs to Saildrone observations in the Bering Sea.

Appendix A

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

Theme	FY 2022 Budget ($K)	FY 2023 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification	66,985	77,529	Contributing
	6,925	7,396	Primary
	73,910	84,925	Total
2. Monitoring of ocean chemistry and biological impacts	5,106	6,144	Contributing
	8,064	10,893	Primary
	13,170	17,037	Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms	1,242	1,470	Contributing
	896	1,125	Primary
	2,137	2,596	Total
4. Technology development and standardization of measurements	55	365	Contributing
	1,200	1,576	Primary
	1,255	1,842	Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems	118	128	Contributing
	784	1,519	Primary
	902	1,646	Total
6. Education, outreach, and engagement on ocean acidification	6	10	Contributing
	1,593	1,519	Primary
	1,599	1,529	Total
7. Data management and integration	2,049	783	Contributing
	1,373	1,525	Primary
	3,422	2,308	Total
8. Other ocean acidification research and monitoring activities	0	111	Contributing
	2,767	2,604	Primary
	2,767	2,715	Total
TOTAL	71,510	52,217	Total Contributing
	23,602	28,156	Total Primary
	95,111	80,376	Grand Total

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

Theme	FY 2022 Budget ($K)	FY 2023 Budget ($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	5	0	Contributing
	53	13	Primary
	58	13	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	371	90	Contributing
	0	0	Primary
	371	90	Total
8. Other ocean acidification research and monitoring activities	0	0	Contributing
	0	0	Primary
	0	0	Total
TOTAL	376	90	Total Contributing
	53	13	Total Primary
	429	104	Grand Total

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

Theme	FY 2022 Budget ($K)	FY 2023 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification	118	23	Contributing
	0	13	Primary
	118	35	Total
2. Monitoring of ocean chemistry and biological impacts	75	0	Contributing
	0	115	Primary
	75	115	Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms	40	90	Contributing
	0	12	Primary
	40	102	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	233	113	Total Contributing
	0	140	Total Primary
	233	253	Grand Total

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

Theme	FY 2022 Budget ($K)	FY 2023 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification	300	300	Contributing
	0	0	Primary
	300	300	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	150	0	Contributing
	0	500	Primary
	150	500	Total
4. Technology development and standardization of measurements	0	200	Contributing
	0	0	Primary
	0	100	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	490	440	Total Contributing
	250	750	Total Primary
	740	1190	Grand Total

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

Theme	FY 2022 Budget ($K)	FY 2023 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification	0	0	Contributing
	300	327	Primary
	300	327	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
	180	304	Primary
	180	304	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
	480	631	Total Primary
	480	631	Grand Total

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

Theme	FY 2022 Budget ($K)	FY 2023 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification	8	1,636	Contributing
	4,673	4,115	Primary
	4,681	5,750	Total
2. Monitoring of ocean chemistry and biological impacts	4,633	6,144	Contributing
	7,823	10,501	Primary
	12,456	16,645	Total
3. Modeling to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms	1052	1380	Contributing
	896	613	Primary
	1,947	1,994	Total
4. Technology development and standardization of measurements	55	165	Contributing
	1,020	733	Primary
	1,075	899	Total
5. Assessment of socioeconomic impacts and development of strategies to conserve marine organisms and ecosystems	78	88	Contributing
	784	1,519	Primary
	862	1,606	Total
6. Education, outreach, and engagement on ocean acidification	6	10	Contributing
	1151	1136	Primary
	1,157	1,146	Total
7. Data management and integration	488	543	Contributing
	1373	1525	Primary
	1,861	2,068	Total
8. Other ocean acidification research and monitoring activities	0	111	Contributing
	2767	2604	Primary
	2,767	2,715	Total
TOTAL	6,320	10,077	Total Contributing
	20,487	22,745	Total Primary
	26,807	32,823	Grand Total

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

Theme	FY 2022 Budget ($K)	FY 2023 Budget ($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	0	0	Contributing
	38	28	Primary
	38	28	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
	38	28	Total Primary
	38	28	Grand Total

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

Theme	FY 2022 Budget ($K)	FY 2023 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification	65,844	74,769	Contributing
	982	1,981	Primary
	66,826	76,749	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	539	Primary
	0	539	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
	342	283	Primary
	342	283	Total
7. Data management and integration	1,190	150	Contributing
	0	0	Primary
	1,190	150	Total
8. Other ocean acidification research and monitoring activities	0	0	Contributing
	0	0	Primary
	0	0	Total
TOTAL	67,034	74,919	Total Contributing
	1,324	2,802	Total Primary
	68,358	77,721	Grand Total

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

Theme	FY 2022 Budget ($K)	FY 2023 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification	0	0	Contributing
	500	500	Primary
	500	500	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	0	Contributing
	0	0	Primary
	0	0	Total
TOTAL	0	0	Total Contributing
	500	500	Total Primary
	500	500	Grand Total

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

Theme	FY 2022 Budget ($K)	FY 2023 Budget ($K)	Activity Classification
1. Research to understand responses to ocean acidification	715	801	Contributing
	470	460	Primary
	1,185	1,261	Total
2. Monitoring of ocean chemistry and biological impacts	393	0	Contributing
	0	86	Primary
	393	86	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	1,108	801	Total Contributing
	470	547	Total Primary
	1,577	1,348	Grand Total