STRATEGIC PLAN FOR FEDERAL RESEARCH AND MONITORING OF OCEAN ACIDIFICATION

A Report by the

INTERAGENCY WORKING GROUP ON OCEAN ACIDIFICATION

SUBCOMMITTEE ON OCEAN AND SCIENCE TECHNOLOGY

COMMITTEE ON ENVIRONMENT

of the

NATIONAL SCIENCE & TECHNOLOGY COUNCIL

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The purpose of the Subcommittee on Ocean Science and Technology (SOST) is to advise and assist on national issues of ocean science and technology. The SOST contributes to the goals for federal ocean science and technology, including developing coordinated interagency strategies and fostering national ocean science and technology priorities. The SOST reports to both the NSTC Committee on Environment and the Ocean Policy Committee.

About the Interagency Working Group on Ocean Acidification

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

About this Document

This document was developed by the IWG-OA of the Subcommittee on Ocean Science and Technology (SOST) and published by NSTC. It meets the requirement of the Federal Ocean Acidification Research and Monitoring Act of 2009 to revise the ocean acidification strategic research plan every five years.

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Acronyms

BOEM	Bureau of Ocean Energy Management
CO_2	carbon dioxide
DIC	dissolved inorganic carbon
DOE	Department of Energy
DOI	digital object identifiers
DOS	United States Department of State
EPA	Environmental Protection Agency
FOARAM	Federal Ocean Acidification Research and Monitoring Act of 2009
FWS	United States Fish and Wildlife Service
FY	fiscal year
GOA-ON	Global Ocean Acidification Observing Network
IPCC	Intergovernmental Panel on Climate Change
IWG-OA	Interagency Working Group on Ocean Acidification
MBON	Marine Biodiversity Observation Network
NASA	National Aeronautics and Space Administration
NEP	National Estuary Program
NIST	National Institute of Standards and Technology
NMSP	National Marine Sanctuary Program
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
NSF	National Science Foundation
NSTC	National Science and Technology Council
OA	ocean acidification
OARS	UN Ocean Acidification Research for Sustainability
OSTP	Office of Science and Technology Policy
pCO_2	partial pressure of carbon dioxide
ppm	parts per million
SDG	UN Sustainable Development Goals
SI	Smithsonian Institution
SOP	standard operating procedure
SOST	Subcommittee on Ocean Science and Technology
TA	total alkalinity
USGS	United States Geological Survey

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Introduction

Ocean acidification (OA) can be detrimental to marine life and to communities that depend on the ocean for food, livelihoods, and security. For example, more acidified water desintigrates coral reefs, so they can no longer protect coastal communities from storm surges or tsunamis. OA also threatens culturally and economically valuable fisheries, such as oysters, mussels, lobster, and salmon, which provide protein and livelihoods for millions of people. New scientific insights, partnerships, methodologies, and tools are critical to understand, mitigate, and adapt to OA. The Biden-Harris Administration has made it a priority to advance OA research and monitoring.

OA occurs when the ocean absorbs carbon dioxide (CO_2) from the atmosphere, changing the ocean's pH (a measure of how acidic/basic water is; lower pH means higher acidity). As CO_2 dissolves in water, it creates carbonic acid, causing the waters to become more acidic. Anthropogenic OA refers to how much pH reduction is caused by human activity. The ocean has absorbed approximately a quarter of the total emitted anthropogenic CO_2, which has caused an estimated reduction in global mean surface ocean pH of 0.1 unit.[1]

OA has increased as CO_2 emissions have increased. Most anthropogenic CO_2 emissions result from burning fossil fuels (oil, gas, and coal).[2] The remainder are from agriculture, deforestation, land use changes, industrial processes such as cement production, and waste. Global CO_2 concentrations have risen from 280 parts per million(ppm) at the beginning of the Industrial era to more than 400 ppm today. This rate of CO_2 increase in the atmosphere is likely faster than at any other time over the last 55 million years.[3] In addition to causing OA, anthropogenic CO_2 emissions threaten food security, national security, human health, and livelihoods.

Freshwater inputs, ocean upwelling, nutrient runoff from land, and coastal atmospheric pollution also result in processes that release or deliver CO_2, acidic nitrogen, or acidic sulfur compounds as byproducts into the oceans, estuaries, and other bodies of water. The contribution of these secondary sources vary by location. Coastal regions associated with ocean upwelling systems such as the West Coast of the United States are especially vulnerable to OA. Coastal acidification is defined as the pH decline resulting from atmospheric CO_2 combined with coastal inputs of CO_2 and other acidifying compounds derived from freshwater sources, nutrient input, upwelling, and local atmospheric pollution.

Over the past two decades, climate change research, laboratory experiments, ocean observations, and examinations of the geologic record have built an understanding of how the changes in ocean carbonate chemistry caused by OA have already affected marine ecosystems and may further influence them in the future.[4] Studies of the geological record suggest that extinction events co-occur with OA events. Research has shown that groups of organisms, like planktonic foraminifera, have already been impacted by the acidification that has occurred since the Industrial Revolution. Laboratory experiments on species from diverse groups, including shellfish, finfish, corals, and algae,

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[1] Gruber, N., et al. (2019). The oceanic sink for anthropogenic CO_2 from 1994 to 2007. *Science, 363*(6432), 1193-1199. doi:10.1126/science.aau5153 ; Orr, J. C., et al.. 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature 437: 681-686.

[2] EPA (2021), Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019. EPA 430-R-21-005. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2019

[3] Gingerich, P. D. 2019. Temporal scaling of carbon emission and accumulation rates: modern anthropogenic emissions compared to estimates of PETM onset accumulation. Paleoceanography and Paleoclimatology 34:329-335.

[4] Cooley, S., Schoeman, D., Bopp, L., Boyd, P., Donner, S., Ghebrehiwet, D. Y., Ito, S. I., Kiessling, W., Martinetto, P., Ojea, E., Racault, M. –F., Rost, B., & Skern-Mauritzen, M. (2022). Oceans and coastal ecosystems and their services. In IPCC AR6 WGII. Cambridge University Press.

show that some organisms are sensitive to acidified conditions. While many primary producers benefit from extra CO_2, studies have shown how some calcium-carbonate-forming species (calcifiers) experience energetic stress when building and maintaining their shells or skeletons, and some crustacean and finfish species experience developmental, physiological, and behavioral issues due to disruption of acid-base regulation. Observations of species in naturally more acidic areas, such as areas of seawater upwelling or volcanic CO_2 vent sites, show impacts to species (e.g., shell structure, molecular markers of stress) and to ecosystems. Often higher acidic areas have less taxonomic diversity and are dominated by fleshy algal species rather than calcifiers (e.g., shellfish, crustaceans, sea urchins, etc.).

OA is further exacerbated by compounding factors, such as increasing ocean temperatures and ocean deoxygenation (the decrease in dissolved oxygen which is necessary to support organisms' basic respiration). For example, higher sea surface temperatures can enhance stratification, meaning that absorbed CO_2 cannot mix into deeper waters. While warmer temperatures can speed up OA, cold temperatures hold higher concentrations of dissolved CO_2. Polar waters are especially vulnerable to the effects of OA because cold water can absorb more dissolved CO_2, and these waters already are naturally closer to undersaturation.

Anthropogenic OA has the potential to change ecosystem services provided by marine environments through both species-specific and ecosystem-level impacts. Already, human social, cultural, and economic systems have needed to adapt to new conditions brought on by OA.[5] For example, over the past 10 years, U.S. oyster hatchery operators have changed their business practices to mitigate the impacts of coastal acidification on hatchery production, resulting in improved yield for many hatchery operators. The cultural and economic implications of potential OA-induced changes in fisheries are an active area of research. Current federally funded efforts are building a better understanding of human vulnerability to OA and related climate change impacts so that research, adaptation, and mitigation can be targeted appropriately. Over the past decade, state- and regional-level efforts on OA have increased tremendously, signaling elevated societal concern about OA as knowledge of the phenomenon and its implications builds.

The Federal Ocean Acidification Research and Monitoring (FOARAM) Act

To guide agency actions that address OA, the Federal Ocean Acidification Research and Monitoring Act of 2009 (FOARAM Act; 33 U.S.C. Chapter 50, Sec. 3701-3708) mandates that the Joint Subcommittee on Ocean Science and Technology (JSOST) (now the Subcommittee on Ocean Science and Technology (SOST)) of the National Science and Technology Council (NSTC) coordinate federal activities on OA and establish an interagency working group. The Interagency Working Group on Ocean Acidification (IWG-OA) was chartered by the JSOST in October 2009 and includes agencies that have mandates for research and/or management of resources and ecosystems likely to be impacted by OA. Biennial reports required by the FOARAM Act detail federal OA activities (Initial, Second FY10-11, Third (FY12-13), Fourth (FY14-15), Fifth (FY16-17), and Sixth (FY18-19)). Federal actions on OA are often done in collaboration or partnership with states, Tribes, industry, non-governmental organizations, and/or academia.

[5] Barton, A., Waldbusser, G. G., Feely, R. A., Weisberg, S. B., Newton, J. A., Hales, B., ... & McLaughlin, K. (2015). Impacts of coastal acidification on the Pacific Northwest shellfish industry and adaptation strategies implemented in response. *Oceanography*, *28*(2), 146-159.

The FOARAM Act explicitly calls for developing a strategic research plan to guide "federal research and monitoring on ocean acidification that will provide for an assessment of the impacts of ocean acidification on marine organisms and marine ecosystems and the development of adaption and mitigation strategies to conserve marine organisms and marine ecosystems".[6] The NSTC published the first Strategic Plan for Federal Research and Monitoring of Ocean Acidification in 2014. The present document serves as the required 5-year update and revision to this 2014 document and meets the expanded scope of the document required by the Coordinated Ocean Observations and Research Act of 2020. The 2014 Strategic Plan and this new Strategic Plan focus on the seven priority themes identified in the FOARAM Act: (1) research; (2) monitoring; (3) modeling; (4) technology development; (5) socioeconomic impacts; (6) education, outreach, and engagement strategies; and (7) data management and integration. The new Strategic Plan is organized around these themes in the order in which they are presented in the FOARAM Act and consistent with previous FOARAM deliverables. The plan details multiple objectives under each theme as well as actions to support the objectives. However, not all priorities in the 2014 Strategic Plan are retained in this document. The shift between the two Strategic Plans represents refinement of OA science, better incorporation of some fields of work (e.g., social sciences, remote sensing, OA mitigation through marine carbon dioxide removal), and acknowledgement of current scientific and bureaucratic priorities. Many of the objectives and actions listed in this Strategic Plan are interconnected, reflecting the interdisciplinary nature of OA research and federal OA activities. Each action indicates whether it is new, revised, or the same as the action in the 2014 Strategic Plan. Each action includes a desired timeline for completion, defined as follows: *short term* less than two years, *medium term* two to five years, *long term* five to ten years, and *ongoing* if expected to be continual or repeated over time horizon of this Plan. Each action includes a list of relevant agencies, with the recommended lead agency or agencies listed first, but does not prescribe a specific approach. These lists of relevant agencies are not meant to be exhaustive or limiting. Participation by additional agencies not listed will benefit many actions.

This plan is complementary to the 2023 Ocean Climate Action Plan (OCAP)[7], which features ocean-based climate mitigation and adaptation actions that address the goals of creating a carbon-neutral feature, accelerating nature based solutions, and enhancing community resilience to ocean change. OCAP recognizes addressing OA as a priority item and also introduces strategies to utilize the ocean to reduce emissions. While a global solution to OA requires rapidly stabilizing and reducing atmospheric CO_2, levels, this strategic plan expands on the full scope of actions taken by the government to address OA.

Theme 1. Research to Understand Responses to Ocean Acidification

Over the past decade, research efforts have built considerable understanding of how marine species populations, ecosystems, and biogeochemical processes respond to OA alone and acting in a multi-stressor framework (which includes the many impacts of climate change on the ocean, such as warming, sea level rise, and increased hypoxia; nutrients and chemical pollution; and other anthropogenic influences). This accumulation of new research has contributed to a deeper and more nuanced understanding of OA; it remains clear that OA has the potential to threaten whole marine ecosystems and the services they provide. Sound science is required to inform the development of effective mitigation strategies to build the resilience of economically important organisms, key marine ecosystems and habitats, and the communities that rely on them.

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[6] Federal Ocean Acidification Research and Monitoring Act, 33 U.S.C. Chapter 50 § 3704

[7] The Ocean Policy Committee (2023). Ocean Climate Action Plan. Executive Office of the President of the United States. https://www.whitehouse.gov/wp-content/uploads/2023/03/Ocean-Climate-Action-Plan_Final.pdf

Although substantial progress has been made since the last Strategic Plan was released, three critical biological research objectives remain. More research is needed to better inform models and improve predictions of: 1) the Earth system response to OA; 2) the impacts of OA on marine populations and communities; and 3) the capacity of organisms or communities to acclimate or adapt to the changes in ocean chemistry induced by OA. Similarly, some of the most significant research challenges identified over five years ago remain: to separate the impacts attributable to OA versus from other environmental stressors, to estimate the synergistic effects of OA within a multi-stressor framework, and to aptly predict future conditions under climate change that threaten ecosystems, communities, and economies that depend on marine ecosystems. Challenges also remain in applying laboratory findings to real-world projections of species, populations, ecosystems, and biogeochemical cycles.

Objective 1.1: Develop foundational information on the sensitivity of marine organisms to ocean acidification within a multi-stressor framework

Research has revealed that many marine species are sensitive to ocean chemistry changes associated with OA. However, responses to OA are often further influenced by simultaneous exposure to climate change and other anthropogenic stressors, such as warming, hypoxia, and eutrophication. While work addressing this objective has been initiated, it is still far from complete. The number of species whose sensitivities has been characterized is small in comparison to the overall diversity of marine life. In addition, research utilizing multi-stressor frameworks, addressing multiple interacting factors (such as sea level rise and hypoxia) is scarce. Results from studies of organisms are fundamental for progress in other themes.

Action 1.1.1. Quantify changes in physiological, developmental, and molecular processes in marine organisms [Revised from 2014 Plan]

Characterizing how OA in a multi-stressor framework influences physiology, survival, reproduction, and other life-history characteristics of marine species is a first step to understanding impacts to marine species and, in turn, food webs. Results from this action are essential to parameterize models that predict population dynamics (Actions 1.1.2, 1.3.1, 3.1.2, 3.3.1). Lab and field studies designed to evaluate the physiological mechanisms that underlie species' responses to OA help characterize species vulnerability and will likely rely on the rapidly developing applications of genomic-enabled approaches (i.e., genomic, proteomic, transcriptomic, metabolomics tools collectively referred to as 'omics). In turn, 'omics results could be developed as reliable biomarkers of OA influence and stress on marine populations (Action 1.3.1), enable the development of new biological sensors (discussed under Theme 4), and better integrate monitoring of ocean biology into existing observing systems (Theme 2). [Ongoing; Leads: NOAA and NSF]

Action 1.1.2. Scale individual biological response information to the population level using models, syntheses, and multi-generational, complete life-cycle laboratory studies [New]

In isolation, knowledge of organismal sensitivity to OA in a multi-stressor framework (Action 1.1.1.) is insufficient to predict how wild populations and ecosystems will respond. The incorporation of species' physiology and biology into organismal, population, and community models will be crucial for projecting species-specific and ecological impacts. Such efforts require information from a variety of laboratory, field, and *in situ* approaches described in Themes 2 and 4 and will provide information critical for modeling efforts discussed in Themes 3 and 5. [Ongoing; Leads: NOAA and NSF; EPA]

Action 1.1.3. Conduct research to identify potential candidate species for ecosystem-level monitoring that can serve as indicators for early warning purposes and increase the capacity for long-term monitoring [Revised from 2014 Plan]

To date, specific population changes directly attributed to OA have not yet been identified or quantified. While populations are almost certainly undergoing changes in response to OA, the absence of explicitly coordinated chemical and biological surveys undermines researchers' ability to detect OA-induced impacts. Combining information on species sensitivity, food web interactions, and changes in species' abundance and distribution is needed to identify a narrowed set of indicator species for detecting and quantifying the ecological effects of OA. Candidates for indicator species may include ecologically significant species, species with particularly sensitive life-cycle stages, and species that have been well-characterized by genomic studies. [Ongoing; Lead: NOAA; EPA]

Action 1.1.4. Develop and/or implement community-accepted best practices for research focused on organism response [New]

Effective interdisciplinary research requires that the various approaches used by researchers are sound and statistically robust. Limitations of any approach or observational errors and their associated interpretations should be clear so that data or results can be exchanged and used by others with confidence. Challenging the interdisciplinary research community to develop quality assurance protocols and widely-used approaches is also essential to support modeling efforts that integrate an array of results and observations. Such model simulations aim to characterize ecosystem response to OA and guide society actions (Theme 3). Efforts related to this action, which overlap in part with Theme 4 include: 1) developing experimental and observational approaches to assess the effects of multiple drivers on organisms, 2) identifying issues related to the collection and interpretation of genomic-enabled approaches, while recognizing that this is a rapidly developing area of research, and 3) defining metadata essential to support data created from these and other organism-focused research efforts (Theme 7). [Ongoing; Lead: NOAA; EPA, NSF]

Action 1.1.5. Develop and/or implement best practices for manipulative and natural field experiments, including in situ *enclosure experiments and vent sites, leveraging natural spatiotemporal gradients [New]*

In situ studies explore the effects of OA on organisms, communities, and ecosystems replete with interactions of a naturally biodiverse system which cannot be replicated in the laboratory. Experimental design for observational studies and manipulative field experiments is detailed in Riebesell et al., 2010.[8] Further effort is needed to identify additional natural environments that are analogous to future and pre-Industrial conditions across a broad range of habitats and that exhibit greater chemical stability and allow for better replication of experiments than currently identified analogs. Field experiments should address hypotheses derived from ecological theory; greater inferential power can be achieved by coupling field and laboratory studies. Studies should ensure both the carbonate system and confounding factors (e.g., light, O_2, nutrients, H_2S) are adequately characterized throughout the duration of the study. [Ongoing; Lead: NOAA; EPA, NSF]

Objective 1.2: Understand the potential for marine organisms to adapt to ocean acidification in a multi-stressor framework

Marine life has existed in the ocean under conditions that are chemically different than today. However, the current rates of acidification and climate change are extremely rapid in comparison to environmental change during other periods in modern geological history. Furthermore, as OA

[8] Riebesell, U., V. J. Fabry, L. Hansson, J. P. Gattuso (Eds.). 2010. *Guide to best practices for ocean acidification research and data reporting*. Luxembourg: Publications Office of the European Union.

progresses, carbonate chemistry alterations are expected to increase, exposing organisms to extreme conditions that may be unprecedented, in combination with mounting other anthropogenic stressors. Scientists are concerned about whether the species that make up Earth's marine biodiversity have the biological and/or evolutionary capacity to keep pace with the rapid changes in ocean environments. Studies designed to identify and quantify species capacity for acclimation (i.e., recovery of function by individuals with prolonged exposure), as well as adaptation (i.e., genetic and epigenetic changes within a population or across populations) are paramount to long-term predictions about the viability of populations and marine ecosystems, including those that are viewed as both ecologically and socio-economically critical (Themes 3 and 5). Some recent research provides optimism: for example, it is now understood that epigenetic influences may allow organisms to change more rapidly than previously thought.

Action 1.2.1. Assess how sensitivity varies within and among species' populations, as well as among related species [New]

Recent research has documented that populations and closely related species can vary considerably in their sensitivity to OA. Such variability has crucial implications for understanding and properly predicting the impacts of OA on populations and marine ecosystems. Knowledge of a population's sensitivity can be coupled with ecosystem predictions to improve management decisions regarding marine resources, particularly as these populations are also adapting to other anthropogenic influences. Characterization of the range of risks faced by populations and/or species to various levels of OA are important inputs for modeling efforts (Themes 3 and 5). [Ongoing; Leads: NOAA and NSF; EPA]

Action 1.2.2. Build mechanistic understanding of why organisms respond differently [Revised from 2014 Plan]

There is a huge diversity of marine life making it challenging for scientists to characterize how a range of marine biota from algae to pelagic fish will respond to OA. A comparative approach to understanding how species respond to OA will yield critical information needed to identify and describe patterns of sensitivity and to extrapolate to unstudied species. In addition, an understanding of the mechanisms behind varying responses to OA, within a multi-stressor framework, is critical to understanding how OA will impact other species and may be used in modeling efforts. [Ongoing; Lead: NSF; NOAA, EPA]

Action 1.2.3. Investigate the potential for physiological acclimation and epigenetic effects of individuals and for evolutionary mechanisms of adaptation of populations [Revised from 2014 Plan]

Analyses of how OA conditions influence selection and fitness, as well as the sub-lethal impacts of OA exposure to individuals, provides insight into the underlying mechanisms and potential for adaptation and acclimation. 'Omics techniques are powerful tools for detecting organismal and population responses to OA and other stressors in marine species and communities. When used in combination with population genetics and traditional ecological surveys, these techniques will likely be helpful in revealing evidence of acclimation and adaptation. 'Omics research also has direct relevance to efforts aimed at mitigating potential impacts of OA via aquaculture, restoration, and, potentially, assisted evolution. [Ongoing; Leads: NOAA and NSF]

Objective 1.3: Understand how ocean acidification, within a multi-stressor framework, drives changes in population, community, and ecosystem structure and affects food web dynamics and biogeochemical cycling

Scaling information from the population and community levels to a regional or ecosystem level is a central next step to understanding changes in food web dynamics and biogeochemical cycles that may result from OA in a multi-stressor framework. Such scaling requires interdisciplinary research, often with large-scale computing, laboratory, and field components. The lines of research to be conducted under this objective inform modeling efforts (Theme 3 and 5) to more effectively direct natural resource management in ways that best mitigate impacts to human cultures, communities, and economies.

Action 1.3.1. Scale species-response research findings to population, food-web, and ecosystem-level response through syntheses, models, observations, and experiments [Revised from 2014 Plan]

Due to the complexity of food webs and the inherent variability within and among populations, information on species sensitivity from laboratory experiments alone is insufficient to understand the potential impacts of OA on populations, food webs, and ecosystems. Rather, a variety of new efforts, including observations from nature and *in situ* experiments, are needed to generate robust projections of change. In order to be fully successful, these efforts will require strengthening model couplings of life history and trophic interactions to link biogeochemical models with food web and ecosystem models, which will be critical outputs for actions listed in Themes 3 and 5. [Ongoing; Lead: NOAA; NSF, EPA]

Action 1.3.2. Collect and evaluate fossil records to quantify historical changes in ocean chemistry and assess organismal and ecosystem response by using a combination of paleo-ecological and geochemical proxy techniques [From 2014 Plan]

The global ocean has experienced OA events in geological history that may serve as analogues for present global OA and provide an improved understanding of climate feedbacks and system response. Paleo studies also have the potential to quantify the progression of OA since the Industrial Revolution and prior to the initiation of wide-spread observations of ocean carbonate chemistry (1980s), thereby closing the gap on the incomplete observational time series. [Ongoing; Leads: NSF and USGS; NOAA, EPA]

Action 1.3.3. Conduct research on biologically produced calcium carbonate minerals, sediments, and structures to improve understanding of their thermodynamics under current and projected future seawater conditions [Revised from 2014 Plan]

A great deal of OA research has focused on its impacts on the formation and dissolution of calcium carbonate minerals that are produced by numerous marine organisms, including corals, bivalves, and plankton. Calcium carbonate minerals, sediments, and structures are typically biogenic in origin and define underwater topography in many regions, such as reefs. Recent research shows these features are changing rapidly in some ecosystems, potentially due, in part, to OA. Additionally, efforts to infer ecosystem processes from estimates of dissolution and calcification are promising. Formation and weathering of calcium carbonate minerals play an important role in regulating atmospheric CO_2 on geological time scales, so knowledge about these rates informs both hindcasting and forecasting of the evolutionary and adaptive potential of Earth’s biota. [Ongoing; Lead: NSF; NOAA, USGS]

Action 1.3.4. Quantify how effects on phytoplankton and zooplankton may change the transfer of carbon from the ocean surface to its depths [Revised from 2014 Plan]

CO_2 incorporated by phytoplankton in surface waters is consumed and metabolized through actions of the pelagic food web. During this process carbon may be transferred to depth in the ocean by various biological processes referred to as the "biological pump." This and other aspects of the carbon cycle are coupled with other biogeochemical cycles, particularly oxygen and nitrogen cycling. Understanding the actions of the biological pump and coupled biogeochemical cycles is particularly relevant to understanding whether ocean regions are sources or sinks for atmospheric CO_2, whether areas of low oxygen and low pH are increasing in subsurface waters, and how OA will affect marine ecosystems and living marine resources. OA may influence the efficacy of the biological components of the oceanic carbon cycle to remove CO_2 from the atmosphere and sequester it in the ocean long-term. This area of research is particularly relevant for evaluating some primary production focused on marine carbon dioxide removal approaches. [Ongoing; Leads: NOAA and NSF; NASA]

Action 1.3.5. Determine how altered biogeochemical processes at the organism, community, and ecosystem scale may change iron, nitrogen, oxygen, phosphorous, silicate, and sulfur cycles [Revised from 2014 Plan]

Non-carbon nutrient cycles are likely to be influenced by biogeochemical processes that are altered by OA. In particular, nitrogen and oxygen cycles are important for water quality and natural resource management. An improved understanding of how OA will affect these non-carbon cycles is important for developing mitigation and minimization strategies in resource management. [Ongoing; Lead: NSF; EPA, NOAA]

Theme 2. Monitoring of Ocean Chemistry and Biological Impacts

A coordinated, interdisciplinary, multinational approach for observing and modeling OA in estuarine, coastal, and open-ocean environments is critical to understand its drivers and impacts on marine ecosystems. Local, regional, and global observation networks have been built to provide the data necessary for robust ecological, economic, and cultural projections of future impacts of OA, which will be critical to inform policymakers, managers, and local stakeholders' decisions. These networks maximize collaborations and leverage planned and existing observing assets, nationally and internationally, to facilitate OA monitoring. This includes enabling monitoring that is conducted in concert with process studies, manipulative experiments, field studies, and modeling.

The following objectives, to be addressed over the next five years, focus on enhancing open-ocean carbon monitoring activities and expanding these networks into coastal and estuarine regions where it is essential to understand and predict responses of marine biota to ocean and coastal acidification, as well as changes in ecosystem processes, biogeochemistry, and climate feedbacks.

Objective 2.1: Maintain and enhance chemical and biological observing assets and determine where these assets should be expanded to better understand the status and progression of ocean acidification in coastal waterways, estuaries, and the ocean

On the national scale, several agencies conduct ocean and coastal acidification monitoring. A description of existing observing systems is shown in the box below. For example, NOAA's Ocean Acidification Program's monitoring network includes repeat hydrographic surveys, ship-based surface observations, and time series stations (mooring and ship-based) in the Atlantic, Pacific, and Arctic Oceans,[9] and the Gulf of Mexico.

Examples of existing, major national observing programs that collect time-series ocean and coastal acidification measurements at fixed stations

- NOAA operates carbon time-series stations that measure physical and chemical parameters at 37 locations in open-ocean and coastal waterways. In addition to these, NSF supports long-term open ocean time series at two sites near Bermuda and Hawaii.
- OceanSITES is a worldwide system of long-term, deepwater reference stations that measure dozens of variables and monitor the full depth of the ocean with 30 surface and 30 subsurface arrays. OceanSITES moorings are an integral part of the Global Ocean Observing System. Satellite telemetry enables near-real-time access to OceanSITES data by scientists and the public.
- The Ocean Observatories Initiative has constructed a networked infrastructure of science-driven sensor systems to measure physical, chemical, geological, and biological variables in the ocean and seafloor. The network includes coastal and open-ocean assets adjacent to the United States, as well as global assets elsewhere in the world's ocean, particularly the high latitudes.
- The Integrated Ocean Observing System is a federal, regional, and private-sector partnership that collects and delivers valuable oceanographic data along our coasts.
- The National Association of Marine Laboratories is a nonprofit organization representing marine and Great Lakes laboratories. Member institutions have long-term data sets for various physical and biological parameters as measured from docks, water intake systems, or frequently monitored shallow-water sites.
- The EPA National Estuary Program (NEP) is a federal program established to improve the quality of 28 estuaries of national importance distributed across the U.S. coastline. The EPA works with States to maintain high water quality in these estuaries and can incorporate new instrumentation and methods for monitoring acidification and its effects in estuaries. Nine of the NEPs currently conduct coastal acidification monitoring using continuous sensors.
- The NOAA/National Ocean Service National Estuarine Research Reserve System is a network of protected areas in U.S. coastal regions with long-term water quality monitoring systems designed to monitor physical, chemical, and biological parameters.
- The NOAA/National Ocean Service National Marine Sanctuary Program (NMSP) is comprised of 14 marine protected areas. NMSP monitoring activities are comprised of efforts targeting individual and multiple sites.
- The Long-Term Ecological Research Network is supported by the National Science Foundation and is used to study ecological processes over long temporal and broad spatial scales at a variety of land-based and marine locations. Some of the marine sites are suitable for monitoring ocean acidification processes.

On the global scale, the Global OA Observing Network is a long-term observing network dedicated to monitoring OA, understanding its biological effects, and supporting forecasts allowing for adaptation

[9] Interagency Arctic Research Policy Committee of the National Science and Technology Council. 2016. Arctic Research Plan FY2017-2021. Executive Office of the President of the United States, pp. 77.

to OA (Figure 1). The Global OA Observing Network data portal (http://portal.goa-on.org) provides metadata for a variety of assets, and some limited data products and visualizations of data streams.

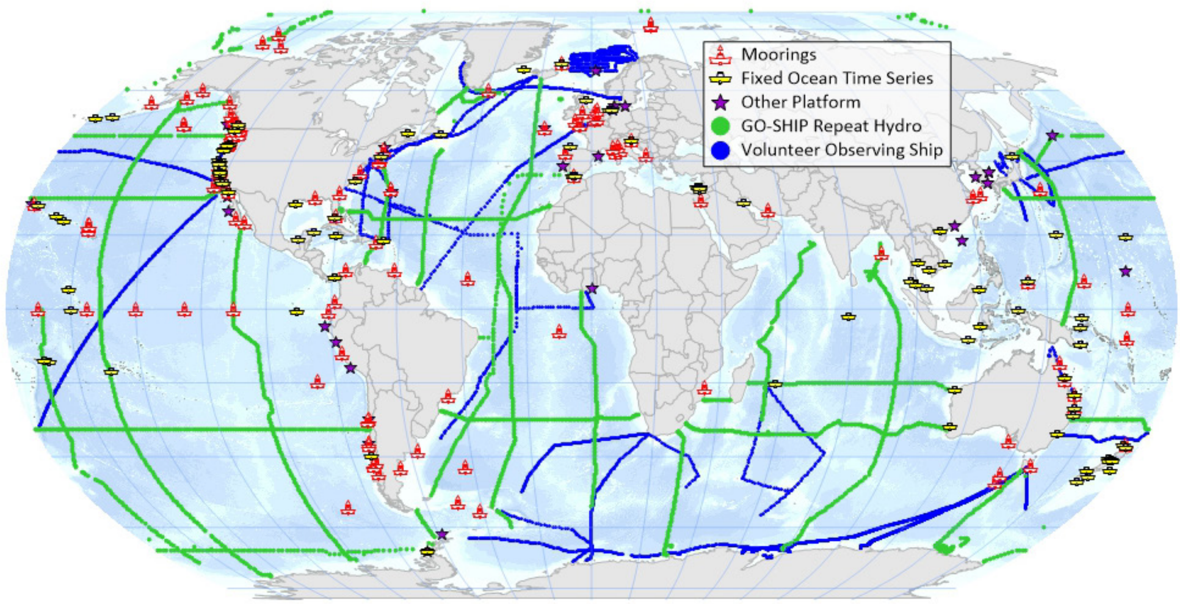

Figure 1. The Global Ocean Acidification Observing Network is collaborative with other open-ocean and coastal observing networks (after Tilbrook et al., 2019 [10]).

Carbonate chemistry observations now can be measured routinely onboard ships and on moorings and floats in open water systems, as well as in estuarine and coastal systems. Maintaining existing assets and sharing methodologies and collected data from coordinated local, regional, and global observation networks is paramount and will further and solidify understanding of the impacts attributable to ocean and coastal acidification. Sharing this information is critical for validation of sensors, development of proxy methods, assessment of accuracies, and general advancement of the equipment. The scarcity of biochemical *in situ* measurements limits the ability to quantify OA on a global scale. The limited coverage of *in situ* platforms does not resolve coastal and mesoscale features. While there is a need to increase monitoring in nearshore environments with differing levels of salinity and riverine input, calibrating equipment for these environments is challenging. Both *in situ* and remotely sensed biological monitoring can be improved through a strategic approach that enables direct comparison of the impacts of OA across different ecosystems, including studies that address whether or not OA 1) leads to increased autotrophic production, 2) reduces heterotrophic production, 3) causes fundamental changes in community structure and biodiversity, 4) changes the ratio of inorganic to organic carbon in pelagic and benthic systems, or 5) leads to altered rates of species and community adaptation. The monitoring prioritization plan, required by the Coordinated Ocean Observations and Research Act of 2020, will take into account gaps identified in this document.

[10] Tilbrook, B., E. B. Jewett, M. D. DeGrandpre, J. M. Hernandez-Ayon, R. A. Feely, D. K. Gledhill, L. Hansson, K. Isensee, M. L. Kurz, J. A. Newton, S. A. Siedlecki, F. Chai, S. Dupont, M. Graco, E. Calvo, D. Greeley, L. Kapsenberg, M. Lebrec, C. Pelejero, K. L. Schoo and M. Telszewski. 2019. An Enhanced Ocean Acidification Observing Network: From People to Technology to Data Synthesis and Information Exchange. Frontiers in Marine Science, 6(337). doi:10.3389/fmars.2019.00337

Action 2.1.1. Identify the existing chemical and biological ocean acidification observing assets and their technology, methods, measurement parameters, data collected, and other relevant information. Ensure the information, including the data collected, is integrated into global data portals. Identify general barriers to maintaining observing assets and provide information, such as available national and regional funding sources [Revised from 2014 Plan]

The identification of existing assets across the agencies in all regions will improve the understanding of the capabilities of current observing stations, where synergies could be made, gaps may exist, or where technology development is needed. Some states, Tribes, and regional organizations that conduct monitoring have developed or contributed to inventories, but not all geographic areas have assessed their monitoring assets. The regional Coastal Acidification Networks are valuable resources to ensure that the agencies have a good understanding of existing assets on regional scales. Several Integrated Ocean Observing System Regional Associations, in partnership with NOAA's Ocean Acidification Program, coordinate regional coastal acidification networks. Each network works with a variety of partners, such as state agencies, researchers, industry, tribal members, and concerned citizens, to assess how changes in ocean and coastal chemistry are manifested in the region, identify gaps, and develop mitigation strategies. The West Coast states, through the West Coast Ocean Acidification Task Force, have inventoried regional chemical and biological OA observing assets from California to Alaska, and some states are undergoing prioritization exercises for potential new assets. [Ongoing; Leads: NOAA and NSF; BOEM, EPA, USGS]

Action 2.1.2. Based on an understanding of existing assets (potentially facilitated by the Coastal Acidification Networks*) from Action 2.1.1 and informed by Observing System Simulation Experiments from Theme 3, evaluate the geographical extent and capabilities of existing monitoring systems in regions and habitats where ocean acidification effects are most likely to occur, and subsequently identify monitoring assets which should be utilized and/or expanded. Prioritize regions and habitats where new systems may be warranted [Revised from 2014 Plan]*

The addition of carbonate chemistry and biological measurements to national monitoring networks is an important step. Carbon observing networks are at an early stage of development for coastal and estuarine environments. Therefore, development of new long-term monitoring systems should be encouraged to fill any data collection gaps identified in priority areas such as high-latitude regions, upwelling regions, warm and cold-water coral reefs, the full water column, and in coastal regions and estuaries where less is understood about the temporal and spatial variability of acidification. The prioritization of assets could be accomplished by working closely with federal, regional, state, and other entities to develop monitoring programs for OA studies in state/Tribal waters, where variability is high and future changes are expected to occur rapidly. [Ongoing; Lead: NOAA; BOEM, EPA, DOE, NSF, USGS]

Action 2.1.3. Expand coastal acidification monitoring in nearshore and estuarine areas, including in the Great Lakes. Identify and deploy monitoring instrumentation in coastal and estuarine sites to extend the carbonate chemistry and biological monitoring parameters for these shallow water systems [New]

Quantifying the impacts of ocean and coastal acidification in estuarine habitats is complex due to the many natural and human processes affecting acidification of these systems. However, determining the role of anthropogenic factors is essential to understanding the spatial and temporal dynamics and the regional drivers of acidification and ultimately predicting the vulnerability of these ecosystems. Specifically, there is a need to understand the effects of local atmospheric inputs, riverine inflow, local pollution inputs (e.g., wastewater, urban stormwater runoff, agricultural runoff), upwelling, and other factors that can exacerbate the effects of near-shore acidification in critical ecosystems. Additionally, while many of the sensors that measure carbonate chemistry parameters have been used extensively in the open ocean, their use in the estuarine environment is novel and challenging due to biofouling, tidal influence, seasonal and diel variability, and other factors and will benefit from technology development and standardization (Theme 4). Further expanding acidification monitoring in near-shore and estuarine areas will help fill the existing knowledge gap and push the current technology to perform in such a challenging environment. The Great Lakes represents one area that has not historically been monitored for ocean and coastal acidification. Evaluating the efficacy and impacts of methods for sequestering carbon in nearshore environments, such as alkalization of power plant effluent and enhancing submerged aquatic vegetation, will require expansion of carbonate chemistry monitoring efforts. [Ongoing; Lead: EPA; NOAA, NPS, USGS]

Action 2.1.4. Expand open-ocean and continental shelf measurements by deploying new ocean acidification monitoring instrumentation on research ships, volunteer observing ships, moorings, fixed stations, and autonomous floats and gliders [Revised from 2014 Plan]

Based on the prioritization in Action 2.1.2, OA monitoring will need to be expanded to high-latitude regions, upwelling regions, warm- and cold-water coral reefs, the full water column, and other areas where less is understood about the temporal and spatial variability of acidification. It will be important to evaluate existing national monitoring networks and identify opportunities to deploy new OA monitoring instrumentation on research ships, volunteer observing ships, moorings, and autonomous floats and gliders (Theme 4). [Ongoing; Lead: NOAA; BOEM, EPA, NSF, USGS]

Action 2.1.5. Expand ocean acidification monitoring as necessary to understand the impacts of emerging ocean technologies and ocean uses [New]

Recognition is growing that removing CO_2 from the atmosphere is required to meet targets related to protecting human and ecosystem welfare from the largest impacts of climate change and OA. As new marine CO_2 removal technologies are developed, there will be a need to support the expansion of the carbon chemistry monitoring network to track changes in carbon and acidification. Additionally, as new uses are developed in the ocean, such as the deployment of offshore energy, impacts to upwelling and carbonate chemistry need to be observed to understand potential impacts related to ocean acidification. [Ongoing; Lead: DOE, NOAA; BOEM, NSF, EPA]

Objective 2.2: Continue global leadership in monitoring of ocean carbonate chemistry conditions and biological impacts of ocean acidification

The United States plays a critical role in the Global OA Observing Network (GOA-ON) as the premier international, long-term collaborative observing network to monitor OA, understand its biological effects, and support forecasts allowing for adaptation to OA. GOA-ON and the Marine Biodiversity Observation Network (MBON) of the Group on Earth Observations seek to collaborate to enable the collection of observations to support understanding of biological impacts from OA and the effects of biological processes on OA. While the GOA-ON data portal contains primarily chemical and physical variables at present, there is a desire to have interoperability with biological data portals; this presents an opportunity for MBON and GOA-ON communities to develop shared approaches through collaboration.

Action 2.2.1. Support and build capacity of the Global Ocean Acidification Observing Network [New]

The network of OA observations is expanding in open-ocean and coastal sites utilizing ships, moorings and biogeochemical Argo floats in deeper water, but collection of concurrent biological observations at those sites is more limited. Emphasis should be placed on simultaneous collection of chemical and biological observations, particularly with respect to marine calcifiers, which have already demonstrated *in situ* negative effects. Identification and development of suitable indicators, combined with the integration of sustained observations from GOA-ON and MBON, would allow for long time series observations at specific locations where measurements of biological community composition and activity are collected in tandem with hydrographic and biogeochemical variables. [Ongoing; Lead: NOAA; DOS, NSF, USGS]

Action 2.2.2. Contribute to global assessments of ocean acidification and its impacts through the World Ocean Assessment and reports of the Intergovernmental Panel on Climate Change [New]

The Regular Process for Global Reporting and Assessment of the State of the Marine Environment, including Socioeconomic Aspects (a.k.a., World Ocean Assessment) is a global effort accountable to the United Nations General Assembly charged with regularly reviewing the environmental, economic, and social aspects of the world's ocean, both current and foreseeable, in order to enhance the scientific basis for policymaking. The World Ocean Assessment (I and II) includes a chapter that examines the physical and chemical state of the ocean, which includes analysis of global OA; U.S. scientists serve as contributing members of the team charged with compiling research and writing this chapter of the World Ocean Assessment.

The Intergovernmental Panel on Climate Change (IPCC) is an intergovernmental body charged with assessing the science related to global climate change. IPCC reports provide policymakers with regular comprehensive updates on the state of knowledge on climate change, its current and future risks, and potential response options, including information related to OA. U.S. scientists, including many from federal scientific agencies, are key contributors to IPCC reports as authors and reviewers, providing technical input and scientific expertise. [Ongoing; Lead: NOAA; EPA, DOE, DOS, NASA, NSF, USGS]

Objective 2.3: Maintain and expand efforts to link chemical observing data to the biological impacts of OA

Carbonate chemistry measurements made contemporaneous with biological measurements, such as biota biomass, physiological responses of sentinel species, population-level dynamics, and community-level effects. are critical to assess the biological response to OA in the ocean and along coasts. There is an important need to incorporate a process for identifying issues to be addressed by current biogeochemical and biological indicators (Theme 1), and guidelines for further development and vetting of new indicators (Theme 4). These biogeochemical and biological indicators for specific sentinel species should be focused on characterization of effects with a view towards major long-term ecological or economic consequences, be responsive to OA over other environmental variables, have the power to detect meaningful differences, and be applied at fairly broad spatial scales with relatively low cost.

Action 2.3.1. Continue to foster closer connections between scientists to provide pertinent information about carbon chemistry of waters where species being studied reside naturally [From 2014 Plan]

Seek to collaborate to enable the collection of observations to support understanding of chemical changes and biological responses due to OA, and the effects of biological processes on OA. This multidisciplinary approach is needed to understand how OA affects ecosystems and marine living resources. [Ongoing; Lead: NOAA; EPA, NSF, USGS]

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

Ocean modeling has advanced rapidly during recent decades with the inclusion of biogeochemical models embedded in three-dimensional general circulation models. Using these embedded biogeochemistry models, the community has progressed towards simulations of the global carbon cycle, and ultimately towards a predictive capacity that includes changes in the carbon cycle as a function of changes in global temperature, ocean circulation, ocean biogeochemistry, and terrestrial and atmospheric inputs. Models are valuable tools for many aspects of ocean and coastal acidification research and monitoring. In this Theme, models are highlighted for their use in interdisciplinary work linking acidification with chemistry, physics, ecosystems, and society.

Modeling efforts that permit exploration of species adaptation capacity and account for species behavior can be used to characterize organism and ecosystem response to OA and evaluate management strategies in an acidifying ocean. There are significant scaling issues that complicate linkage of biogeochemistry ocean general circulation models with finer-scale ecological organization and high spatiotemporal heterogeneity of coastal environments. Solutions to these scaling problems will both inform and depend upon results from observation programs and biological/ecological studies (Themes 1 & 2). Ultimately, these issues are not specific to ocean modeling; it is challenging in general to identify and capture appropriate scales of ecosystem complexity in a computer model and then project how the system will respond.

Considerable progress is required to reach the level of accuracy needed for decision support, because it often requires shorter time-space-scales (i.e., shorter data latency) than many current models can realistically provide. There is a general need for developing fit-for-purpose regional models, such as Regional Ocean Modeling System or Finite Volume Community Ocean Models that are nested within, or use output from biogeochemistry ocean general circulation models, in order to manage amid a dynamic and changing Earth system and inform human social adaptation strategies. These regional-scale hydrodynamic models are frequently integrated into estuarine water-quality models for decision support under the Clean Water Act. Investment in this area of modeling is essential to understanding these complex systems across differing observing scales (Theme 2) exhibiting a range of biotic response (Theme 1). Similarly, there is strong interest in Integrated Assessment Models that are primarily econometric (Theme 5), but have increasingly included ecological components to capture the interaction between ecosystems and economics. Such models are now being applied to OA impacts on coastal economies.

Objective 3.1: Provide guidance for research and ocean observation efforts

Scientific understanding of the responses of organisms to OA is improving (Theme 1), making it possible to model organismal responses to an acidifying ocean. Increased collaboration between modelers and other researchers will enhance both model performance and observing system design.

Action 3.1.1. Explore the use of Observing System Simulation Experiments to optimize in situ *and remote sensing ocean acidification observation network design [Revised from 2014 Plan]*

Observing System Simulation Experiments are widely used in some fields to plan the most effective and efficient design for sampling. These tools can be utilized to guide deployment of new observing systems to optimize the goals of OA observing systems. [Ongoing; Lead: NOAA; NASA]

Action 3.1.2. Facilitate communication between modelers, field and lab researchers to improve model predictive capability [New]

Models are reliant on observational and experimental data. When model sensitivities such as particulate-inorganic-carbon parameterization or larval sensitivity to pH are identified, these needs should be clearly communicated to the observational and experimental research communities. Federal funding opportunities will encourage closer collaboration to facilitate improved model parameterization. [Ongoing; Leads: NOAA and NSF; DOE]

Objective 3.2: Understand physical, chemical, and biological linkages related to ocean acidification

Regional models are especially needed for high-latitude open ocean, coral reefs, and coastal regions, which are all vulnerable to coastal and ocean acidification in the near-term. The impacts of acidification in coastal regions are also modified by other anthropogenic stressors, such as nutrient pollution, as well as local hydrodynamics. Models will help resolve these interconnected processes and assess the integrated effects on ocean systems.

Action 3.2.1. Invest in and develop multi- and interdisciplinary models to ensure coupling of coastal processes on both sides of the land-ocean boundary, as well as atmospheric and benthic processes [Revised from 2014 Plan]

Couple current sophisticated terrestrial land-use/land-use change models with coastal hydrology and biogeochemistry to provide critical information for regions where humans impact marine systems the most. Use these models to examine the relative contributions to coastal acidification of natural processes, such as marine heat waves and the El Niño Sothern Oscillation, in conjunction with local processes, including benthic community interactions and anthropogenic terrestrial activities. [Ongoing; Leads: NOAA and DOE; EPA, NASA, NSF]

Action 3.2.2. Continue progress implementing key carbonate system tracers and processes in Biogeochemical Ocean General Circulation Models, such as alkalinity, DIC, and dissolution [Revised from 2014 Plan]

Dissolution is key for evaluating the potential for carbon sequestration in the deep sea and impacts on reef and seafloor structure, and requires accurate carbonate chemistry modeling across salinity gradients and at depth. Studies should refine and select appropriate parameterizations for particulate inorganic carbon and couple it with carbonate chemistry, rather than treating them independently. Total alkalinity should be used as a prognostic tracer rather than a diagnostic from salinity measurements. It should be directly calculated so that its effect on organisms and carbon cycling can be accurately defined. [Ongoing; Lead: NOAA; NASA, NSF]

Action 3.2.3. Continue progress on nesting downscaled regional models within global climate models to ensure an understanding and predictive capability of the impact of a variable and changing ocean on ocean biology [Revised from 2014 Plan]

Use high-resolution regional models to realistically represent, for example, coastal upwelling or coral reef hydrodynamics that are smaller than the grid-scale of global models. Confront and evaluate downscaled and regional models with new observation data. [Ongoing; Lead: NOAA; DOE, NASA, NSF]

Objective 3.3: Model the linkages among ocean acidification, ecosystems, and society

There remains a need for ocean resource management and decision support models that inform acclimation and adaptation strategies by projecting habitat shifts and changes to ecosystem services at both global and regional scales. Managing OA-sensitive fisheries and coastal habitats requires a modeling capability that incorporates species response as informed by experiments (Theme 1) and, where possible, validated through field observations (Theme 2). Such models could be employed to support resource managers by projecting potential ecological, cultural, and economic impacts and inform prioritization of research and mitigation efforts.

Action 3.3.1. Develop and improve models that can predict direct and indirect effects of ocean and coastal acidification on culturally, economically, and ecologically important species, communities, and processes [Revised from 2014 Plan]

Ecosystem models, coupled to biogeochemical and hydrodynamic models, are an important tool for forecasting the impact of OA on society. OA is expected to alter ocean chemistry and affect marine resources in ways that will likely cause current management practices to fail to meet their objectives and impede success of fisheries and coastal recreation industries. Incorporating knowledge on species and ecosystem responses to OA – including knowledge about whether these responses combine additively or synergistically with other stressors – into economic, social services, and resource management to guide management decisions will benefit the communities, industries, and economies that rely on marine resources. There is also a need to integrate Indigenous Knowledge into models and assessments of how OA is changing ecosystems. [Ongoing; Lead: NOAA; BOEM, EPA, USGS]

Action 3.3.2. Develop and improve linkages between ecosystem models and socioeconomic models [New]

Continue development of Integrated Assessment Models and other means of assessing the impacts of OA on the socioeconomic well-being of coastal communities. Identify regional fisheries or physical locations most at risk from the effects of OA. [Ongoing; Lead: NOAA; BOEM]

Action 3.3.3. Evaluate ocean acidification impacts on structural habitats and consequences for community resilience to coastal hazards [New]

Coral and oyster reefs create natural infrastructure on the seafloor that serves as a barrier protecting coastal populations from hazards such as storms, waves, and erosion. Long-term impacts of reef degradation and dissolution of carbonates on seafloor elevation and coastal hazards is an emerging need to model socioeconomic consequences of OA impacts to these critical habitats and potential mitigation approaches. [Ongoing; Leads: NOAA and USGS]

Action 3.3.4. Evaluate strategies for mitigating ocean and coastal acidification and the consequences of inaction [New]

Models will assist in evaluating the costs and benefits of proposed mitigation techniques. These tools should also be used to reveal new potential geoengineering approaches to mitigate OA. Simulations under different global change scenarios, in the context of multiple stressors, can be used to compare options and assess the cost and impact of inaction. [Ongoing; Lead; NOAA; BOEM, EPA, DOE]

Theme 4. Technology Development and Standardization of Methods

As with any scientific program, ensuring adequate data quality of measured parameters is critical for OA research, which is interdisciplinary, with many chemical, biological, and physical characteristics that need to be concurrently monitored. Effective OA monitoring and research has benefited from advanced technology and methodological development in recent years including best practices, refined quality control protocols, and new sensor technologies. However, considerable needs remain in each of these areas including achieving affordable, adaptable, and robust instrumentation for continuous autonomous monitoring of OA both in the field and laboratory that can fully characterize changes unfolding within coastal, ocean and freshwater environments at frequencies, depths, and scales most relevant to biological processes to better inform numerical models. Specifically, approaches are needed to better characterize habitats most relevant to species and life-stages demonstrated to be sensitive to OA, including below the mixed-layer depth, at the sediment-water interface, and in environments influenced by freshwater. Improved capabilities are needed to detect biologically meaningful response effects, better avoid type-I and type-II errors, and to achieve appropriate replication for statistically sound conclusions. Other focus areas include ensuring: appropriate, comparable, and standardized methods are further developed; suitable measurement approaches are adopted, where uncertainties are quantified and fit-to-purpose; sensor and other technologies are strategically developed to maximize data quality, coverage, and cost effectiveness; and centers of technical expertise and/or shared community research facilities are maintained and broadly accessible. Remotely sensed data remain underutilized in the ability to infer OA high-frequency dynamics or map long-term changes in habitat response and represents an area of potential growth in coming years. Finally, as carbon dioxide removal techniques are being developed, there is a need to research these technologies and approaches to understand their impacts to the seawater carbonate system and marine environment.

Objective 4.1: Develop, test, and commercialize new seawater chemistry observing technologies

Methods and technologies have been developed for discrete and autonomous inorganic carbon measurements from seawater. Monitoring technology using uncrewed platforms has been developed, including moorings, gliders, autonomous vehicles, floats, and satellites. However, continued efforts need to focus on development of highly reliable, easy-to-use, low-power, inexpensive, robust, adaptable, commercial analytical systems for these platforms that include the full suite of carbon system and supporting chemical variables.

Action 4.1.1. Improve capability to measure chemical variables over space and time, including affordable autonomous sensors, more accessible and affordable high-quality instrumentation and in situ *technologies [Revised from 2014 Plan]*

Progress has been made on development of pH and pCO_2 sensors, but the need for widely available, affordable sensors and continued research, development, and testing remain. In addition, new attention should focus on dissolved inorganic carbon and total alkalinity sensors to improve versatility for use in coastal/estuarine systems, which have highly variable chemistry, and inclusion of better anti-biofouling capacity for field deployments. The NOAA Alliance for Coastal Technologies program should be engaged in evaluation of these new sensor technologies. Development of an additional carbon sensor appropriate for deployment on surface gliders, biogeochemical Argo floats, and profiling gliders should be encouraged. Federal agencies should seek to expedite the transition of all these technologies to commercialization through stronger partnerships with private industry, using mechanisms including the National Oceanographic Partnership Program, agency Small

Business Innovation Research funding, and NSF's Oceanographic Technology and Interdisciplinary Coordination program. [Ongoing; Leads: NOAA and NSF; EPA, USGS]

Action 4.1.2. Integrate existing and new instruments for conducting carbon system analyses onto a variety of platforms including autonomous surface and subsurface vehicles and stationary platforms [Revised from 2014 Plan]

Subsurface water column, deep-, and cold-water deployments have been particularly challenging and require special attention. Depth requirements range from near the surface (few meters) to deep (60+ meters). Performance, analytical capabilities, and science-quality real-time data reporting of gliders, autonomous underwater vehicles, drifters, profilers, and moorings need to be improved to accommodate these challenging environments. The international effort to develop and expand biogeochemical Argo float monitoring to include OA measurement requirements should be supported. [Ongoing; Leads: NOAA and NSF]

Objective 4.2: Develop and validate methods for tracking biological response to ocean acidification

In addition to characterizing the chemical variability and trends within a system, there remains a need to establish well-defined organismal and community metrics for monitoring and assessing species and ecological response that better discerns specific attribution of change.

Action 4.2.1. Further develop standardized methodologies for monitoring long-term biological community response and adaptive capacity to ocean acidification [Revised from 2014 Plan]

Progress has been made in recent years in devising advanced techniques that could be employed for the detection of OA-induced changes to organism and community processes such as the following: coral calcification, density, and extension rates; assessing bioerosion rates; calcareous algae recruitment and accretion; net community metabolism; 'omic' expression; planktonic organism shell dissolution; among others. Continued development of these and other methods need to be streamlined and standardized to allow them to be more systematically incorporated into existing long-term observing programs. [Ongoing; Lead: NOAA; NSF, USGS]

Action 4.2.2. Integrate existing and new instruments capable of acquiring biogeochemical data that can be applied to discern community processes onto a variety of platforms including autonomous surface and subsurface vehicles [Revised from 2014 Plan]

Recent advances have allowed for an extension of the biogeochemical Argo program to begin adopting biogeochemical observations (oxygen, nitrate, pH, chlorophyll, etc.) that will permit a valuable means of linking OA to large-scale changes in global ocean biogeochemical processes which may be altered by or interact with OA. Various sensors have now been demonstrated on a range of platforms (e.g., gliders, moorings). Inclusion of rapid, cost-effective technologies for quantifying abundances of targeted organisms affected by OA remains elusive and should be sought for inclusion in integrated OA observation networks (e.g., GOA-ON). [Ongoing; Leads: NOAA and NSF]

Objective 4.3: Develop and validate methods for improved tracking of modern and historical changes in ocean chemistry

Best methods for many discrete and underway measurements of the inorganic carbon system are well-established and described in guides to best practices and should be followed whenever possible.[11] However, additional measurement techniques are required to improve measurements in diverse coastal environments. Establishing historical context for the current anthropogenic acidification event is critical to assessing its relative severity to past events and understanding how marine ecosystems might be altered under continued acidification over coming decades to centuries. Continued fundamental research is required to develop best practices for use of proxies for paleo-OA environmental conditions and to develop methods and calibrations for measurement of additional ocean chemistry parameters. Looking to the future, new methods and research are needed to assess how proposed approaches for marine carbon dioxide removal (mCDR) affects acidification in ocean ecosystems.

Action 4.3.1. Support the establishment of validated SOPs for additional ocean chemical, physical, and biological measurements [Revised from 2014 Plan]

The development of standard operating procedures, in addition to calibration and validation studies, is needed for alternative water sample preservation methods and measuring. These include the following: organic alkalinity; thermodynamic constants; carbon removal from systems by natural sequestration; baseline carbonate chemistry in historical and ancient oceans; the response of organisms, ecosystems, and carbon cycling to past OA events; appropriate collection and evaluation of historical records of ocean chemistry, geochemical and paleo-ecological response; and accurate measurements of modern and historical calcification and carbonate dissolution. [Ongoing; Lead: NOAA; NSF, USGS]

Action 4.3.2. Calibrate existing paleo-ocean acidification geochemical and calcification proxies and develop new multiple proxy geochemical techniques to reconstruct the full marine carbonate system [Revised from 2014 Plan]

Paleo-OA proxies are chemical signatures found in fossil remains of marine organisms and minerals that can be used to quantitatively reconstruct ocean environmental conditions, the marine carbonate system, and organism and ecosystem response to OA in the geologic past. Boron-based isotope and shell calcification proxies applied in well-preserved fossil records can capture important information about paleo-ocean pH and organism calcification response. However, further research is needed to improve existing proxy calibrations for foraminifera, additional coral and other marine species, as well as freshwater species. Research methods standardization, and best practice guidance needs to be developed for expanding use of boron/calcium ratio proxies for paleo pH and carbonate ion concentration. [Ongoing; Lead: NSF; NOAA, USGS]

Action 4.3.3. Analyze emerging technologies and methods for sequestering atmospheric carbon dioxide into long-term storage in ocean ecosystems [New]

Several carbon dioxide removal techniques could mitigate OA, either through the direct removal of CO_2 from seawater or through the addition of alkaline material. Because these proposed techniques are fundamentally a manipulation of ocean carbon chemistry, observation and projection of their impacts on the Earth system accordingly fall within the purview of this OA research strategy. Before these solutions could be deployed at scale, research is needed to test and communicate the efficacy, impacts, risks, and co-benefits of implementation for ocean ecosystems, marine natural resources, and human communities. New methods must be developed to evaluate and verify the effects that these techniques have on OA and on long-term carbon storage. [Ongoing; Lead: Currently undefined; BOEM, EPA, NOAA, USGS]

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[11] Dickson, A. G., C. L. Sabine and J. R. Christian (Eds.). 2007. *Guide to best practices for ocean CO_2 measurements*: PICES Special Publication 3.
Riebesell, U., V. J. Fabry, L. Hansson and J. P. Gattuso (Eds.). 2010. *Guide to best practices for ocean acidification research and data reporting*. Luxembourg: Publications Office of the European Union.

Objective 4.4: Foster high-quality ocean carbonate chemistry measurements by establishing community-wide quality assurance schemes and increasing availability of analytical resources

The current analytical capacities and expertise in carbon system dynamics, as it pertains to OA, are not adequate in most laboratories. There is a need to further develop and better apply quality assurance protocols and approaches to ensure the availability of the high-quality data that are needed to support policy and management decisions, especially for measurements taken in nearshore and coastal environments.

Action 4.4.1. Continue to support and expand access to distributed centers of expertise that provide routine analytical services, analytical training for the scientific community, and infrastructure that is available for community-use to conduct specific research studies [Revised from 2014 Plan]

As the OA research community grows, additional analytical centers able to analyze seawater with the precision and accuracy needed to detect OA trends, located in both federal and academic laboratories, will be needed to help make analytical services more accessible and to develop expertise in OA issues unique to different regions. Continued OA short courses and web series, taught by experts in the field, are needed to educate the broader community on available techniques, proper analytical methods, and experimental design. [Ongoing; Leads: NOAA and NSF; USGS; NIST]

Action 4.4.2. Support the development of guidance specific to ensuring that researchers are following consistent and appropriate analytical methods with documented quality assurance/quality control procedures [Revised from 2014 Plan]

Documentation of community-supported standard operating procedures for techniques including inter-laboratory comparison exercises to assess accuracy and precision of methods; regular use of certified reference materials to assist in quality control; regular laboratory performance testing using blind samples; and working collaboratively to ensure that high-quality standards are available to the scientific community is needed. [Ongoing; Lead: NOAA; EPA, NSF, USGS, NIST]

Action 4.4.3. Expand inorganic certified reference material development and production efforts to better support the growing ocean acidification community needs [Revised from 2014 Plan]

The need and approach for production of lower salinity ionic strength certified reference materials for Great Lakes and other fresh water and mesohaline studies needs to be assessed. Agency partnerships need to be identified for continued development and production of high ionic strength buffers to help calibrate pH measurements in seawater. International partners need to be engaged for development and production of reference materials for inorganic nutrients. Potential for partnership among Scripps Institution of Oceanography, NIST, and commercial entities needs to be examined for continued production and distribution of certified reference materials, including appropriate business and infrastructure development for continued certified reference material operations. [Long term; Lead: NSF; NOAA; NIST]

Action 4.4.4. Ensure cross-calibration of measurement techniques [From 2014 Plan]

Continue the use of inorganic carbon-certified reference materials produced at the Scripps Institution of Oceanography/UC San Diego for verifying that dissolved inorganic carbon and total alkalinty measurements are consistent with an agreed-upon international standard. Continue international, interlaboratory calibration exercises using methods established during 2013 calibration exercises.[12] Explore development of a certification program for centers of excellence and identification of these certified centers. [Ongoing; Lead: NOAA; EPA, USGS; NIST]

Objective 4.5: Expand the use of satellite observations and emerging remote sensing technologies for observing high-frequency ocean acidification dynamics, associated biogeochemical processes, and tracking changes to impacted habitats

Remote sensing offers a powerful tool for studying surface OA dynamics and its ecological impacts. Surface physical and biological phenomena which influence carbonate system dynamics (e.g., sea surface temperature, salinity, optical properties, primary productivity) are readily available via remote sensing (Figure 2). Satellite data coupled with *in situ* observations can be applied to derive synoptic estimates of OA conditions and governing processes, as well as impacts to ecosystems, and support a diverse range of activities.

Action 4.5.1. Establish satellite-derived global dynamic classifications of pelagic seascapes from remotely sensed variables [New]

Currently, a global beta seascape product exists that incorporates satellite sea surface height, modeled salinity, and satellite ocean color and temperature. This provides a way to relate organisms to their dynamic habitat and track changes within and across ecosystems, including changes related to OA. However, case studies currently remain limited to the coastal regions as part of the U.S. MBON. Methods and applicability of seascapes, and how they relate to better understanding of OA impacts, should be investigated for expansion to pelagic seascapes. [Ongoing; Leads: NASA and NOAA]

Action 4.5.2. Make progress on acquiring satellite data and deriving statistical or quasi-mechanistic algorithms to infer surface ocean carbonate dynamics and driving biological processes from remotely sensed variables [New]

Satellite remote sensing can provide synoptic observations of a range of physical and bio-optical parameters that allow us to understand changes in the Earth at unprecedented temporal and spatial scales. Changes in the distribution of carbonate chemistry within the surface ocean can be derived with remote sensing assets, which can be particularly useful in areas where no *in situ* observations are available. However, the relationships between bio-optical parameters measured by satellite and *in situ* chemistry are complex. Satellite proxies need further algorithm development to improve their utility. Algorithm development can be facilitated by utilizing paired biogeochemical and *in situ* optical measurements from ongoing OA surveys with satellite measurements. Efforts could also be taken to derive surface ocean pCO_2 at suitable spatiotemporal scales (e.g., monthly, 0.5 degree) using surface ocean gridded data synthesis products (e.g., Surface Ocean CO_2 Atlas) applied to remotely sensed data products to produce gridded fields of monthly global sea surface pCO_2. [Ongoing; Leads: NASA and NOAA]

[12] Bockmon, E. E., and A. G. Dickson. 2015. An inter-laboratory comparison assessing the quality of seawater carbon dioxide measurements. Marine Chemistry, 171:36-43.

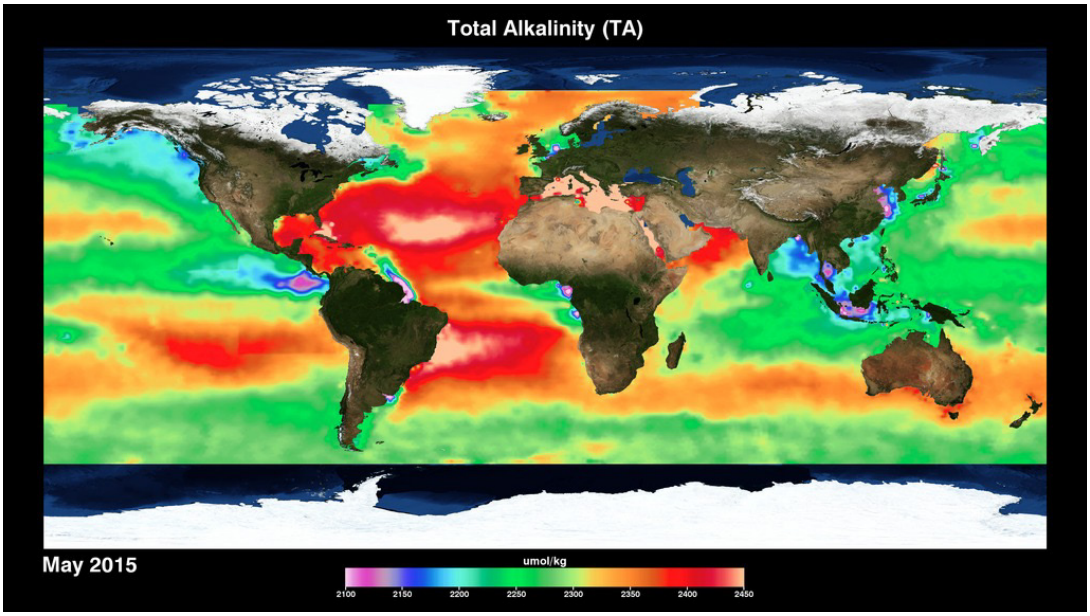

Figure 2. Satellite surface salinity data are becoming key in monitoring ocean carbon cycle, enabling the first space-borne maps of OA. Shown here is monthly surface total alkalinity derived using Aquarius salinity. Credit: NASA

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

Researchers are just beginning to unravel the full effects of increased CO_2 in the atmosphere and the resultant alterations in ocean chemistry and biology and are not yet able to fully understand the consequences that this process will have on society. Increasing understanding of the effects of OA will inform discussions of climate change mitigation and adaptation, thus helping stakeholders and decision makers to respond more effectively. There is also an important opportunity to collaborate with community members on the development of mititgation and adaption strategies; this includes incorporating Indigenous Knowledge.

As the ability to monitor and forecast the physical impacts of OA improves, researchers will also be able to improve assessments of the cultural and economic effects. Based on the current state of knowledge, there are several key areas where the effects of OA are most likely to occur:

- Aquaculture – Hatcheries and grow-out facilities are dependent on careful control of the environment in which their stocks are grown. For saltwater species, ocean water is often pumped in and will have to be monitored and controlled to avoid mortality, increasing the costs of production and/or reducing output. Currently, early life stages of some cultured shellfish occur in coastal waters and may be impacted by acidification.
- Tropical Coral Reef Systems – Coral reef systems are complex and already being damaged by other anthropogenic stressors, like water pollution, destructive fishing practices, and climate change. The addition of OA to these stressors will exacerbate adverse effects on the health of corals and coralline algae. Coral reefs provide habitat for commercial and subsistence fisheries, support tourism and recreation markets, provide protection from coastal flooding and erosion, and contribute to marine biodiversity.

- Marine Fisheries – Culturally and economically valuable finfish may be affected directly by acidifying waters and through the food web. OA is also likely to affect critical habitat for some species, such as alterations in coral and oyster reefs. Wild harvest of shellfish may have to shift to aquaculture production where seawater chemistry can be monitored and controlled.
- Subsistence Shellfish Harvesting and Fisheries – Many of the marine organisms that are most intensely affected by OA contribute substantially to the food, health, identity, heritage, culture, and social ways of life of coastal Indigenous Peoples and their broader social networks inland.

Aggregate measures of economic impacts, such as percentage Gross Domestic Product lost due to environmental damages, are useful summary statistics but tell only part of the story. It is also important to examine how those impacts are distributed across the affected population and in what ways (e.g., livelihoods, health, and cultural practices). Economic impacts of environmental damages can disproportionately affect some state, local, or Tribal governments, geographic locations, or subpopulations of interest including historically disadvantaged communities that may rely on affected species for subsistence harvesting and cultural practices. While economic impact assessments are valuable tools to inform priorities, it should be noted that some values cannot be accurately monetized. Decision makers will require this knowledge as they develop mitigation and adaptation strategies for OA.

The blueprint for building resilience to OA in economies and communities is to first understand how the anticipated organismal and ecological impacts affect human welfare and to let those findings guide the pursuit of strategies to mitigate risk and adapt to the eventual outcomes. The objectives below follow that blueprint to foster the development of effective mitigation and adaptation strategies.

Objective 5.1: Improve understanding of sociocultural and economic risks to U.S. communities due to ocean acidification

Assessing the social and economic impacts of OA involves weighing the near-term costs and impacts of mitigation and adaptation against the mounting costs of unmitigated impacts. Assessing the socioeconomic impacts of OA will require several components, including long-term forecasts of socioeconomic conditions, valuation of market and non-market impacts, integrated assessment modeling, social discounting, and uncertainty analysis. Such an impact assessment would then permit analysis of the priority needs and outcomes, and cost-effectiveness of mitigation and adaptation strategies.

Action 5.1.1. Collect and synthesize existing research on the economic impacts of ocean acidification [New]

A systematic review of the existing studies and quantitative assessment of their estimates would provide the research community with direction for future efforts and possibly a preliminary comprehensive estimate of the benefits of mitigation and adaptation for policymakers and stakeholders. [Ongoing; Leads: EPA and NOAA]

Action 5.1.2. Conduct new non-market valuation and economic impact studies to estimate damages from different impacts of ocean acidification as understanding increases [Revised from 2014 Plan]

Existing studies that value impacts of OA tend to focus on a limited set of impacts and most do so in small study regions. To address a global problem such as OA will require studies that are broader in scope, both in terms of the anticipated impacts and geography. [Ongoing; Lead: NOAA]

Action 5.1.3. Conduct in situ *research to study ocean acidification risks and impacts in existing ecosystems [New]*

Local environmental conditions are highly variable, and many factors that protect against or exacerbate OA effects are not well-understood. *In situ* research in localized areas can be used to validate or improve OA models and can better inform both risk identification and mitigation and adaptation strategies. This Action complements the Actions in Theme 1, focusing on local, *in situ* data collection to generate the information needed to connect habitat-based information with socioeconomic impacts and management. [Ongoing; Lead: EPA; NOAA]

Action 5.1.4. Foster communication and collaboration between natural and social scientists to identify and support human communities that are particularly vulnerable to ocean acidification through co-production of knowledge [Revised from 2014 Plan]

Conduct research at the intersection with traditional knowledge from marine resource-dependent communities, including coastal Indigenous communities. Advance research that includes traditional and local knowledge with coastal ecosystem science from Western science, following the Guidance for Federal Departments and Agencies on Indigenous Knowledge. Assessments surrounding this collaboration would help to better understand change in shellfish and coastal ecosystems resources and how they are affecting these communities culturally and economically. This traditional and local knowledge can help provide a longer-term perspective from the communities who have observed environments and relied on subsistence or supplemental harvesting for generations. [Ongoing; Lead: NOAA]

Objective 5.2: Use the findings of research on the biophysical and socioeconomic impacts of ocean acidification to evaluate mitigation strategies

The most direct way to reduce OA is to reduce the atmospheric concentration of CO_2. This requires sharp reductions in CO_2 emissions, increasing CO_2 sequestration, or both. Agencies and experts engaged in climate change discussions have invesitated strategies to reduce greenhouse gas emissions and have documented these in various federal reports. They include establishment of regulatory standards on emission levels, financial incentives for innovative technology development, tradable permits, increasing energy efficiency, reduction of deforestation, promotion of reforestation, and shifting energy sources from fossil fuels to alternative energy sources. These solutions require an organized and committed international effort that crosses social, cultural, and political boundaries.

Action 5.2.1. Develop integrated models that link physical, biological, and socioeconomic systems to estimate the economic and distributional impacts of ocean acidification and a more comprehensive estimate of the social cost of carbon [Revised from 2014 Plan]

The social cost of carbon is a measure of the economic benefit from a marginal reduction in CO_2 emissions and is used to evaluate the economic efficiency of regulations affecting CO_2 emissions. All estimates of the social cost of carbon and greenhouse gas emissions produced to date quantify damages from climate change but omit impacts from OA. This is a potentially large omission that leads to an underestimate of the social cost of carbon and the benefits from regulations that reduce CO_2 emissions. To more accurately evaluate the economic efficiency of CO_2 emissions policies, OA impacts need to be included in the integrated assessment models used to estimate social cost of carbon. How those impacts are distributed across political boundaries and socioeconomic groups is also important information that integrated models can provide to decision makers. [Ongoing; Lead: EPA; BOEM, NOAA]

Action 5.2.2. Identify ways to quantify the effects of other environmental stressors on the efficacy of mitigation strategies for ocean acidification [New]

Environmental stressors other than acidification can exacerbate the effects of OA on valued marine resources such as coral reefs, seagrass beds, and shellfish. These stressors include urban and agricultural runoff, sedimentation, and destructive fishing practices, among others. An accurate accounting of the cumulative influence of these other stressors on ecosystem resilience and survival of valued resources is needed to evaluate both the need for and the success of OA mitigation efforts. [Ongoing; Lead: NOAA; BOEM, EPA]

Objective 5.3: Develop adaptation strategies and aid implementation

Some degree of further OA is inevitable regardless of mitigation efforts. Adapting to or coping with the resulting impacts will become necessary for some parts of the population and sectors of the economy. Adaptation is a risk-management strategy that has costs and is not foolproof. The effectiveness of any specific adaptation requires consideration of the expected value of the avoided damages against the costs of implementing the adaptation strategy. Additionally, OA adaptation strategies should, if possible, complement strategies developed for other climate, societal, and ecosystem stressors.

Action 5.3.1. Improve communication between researchers, stakeholders, Tribal nations, and decision makers to develop efficient adaptation strategies [Revised from 2014 Plan]

Making the economy and communities resilient to the effects of OA requires input from researchers to identify vulnerable human dimensions and sectors of the economy, from stakeholders and Tribal nations to develop options for adaptation, and from decision makers to ensure the resources are available to implement those strategies. Multilateral, structured, and frequent conversations are the most effective way to achieve this objective. [Ongoing; Lead: NOAA; EPA, USGS]

Action 5.3.2. Develop decision support tools to assist national, Tribal, state, and local governments in developing management options and understanding their implications [Revised from 2014 Plan]

The best adaptation strategy for an individual, business, or community will depend on too many factors to develop a uniform response for large sectors of society. Creating tools that stakeholders can use to navigate the complicated decision process will make adoption more likely and communities and economies more resilient. [Ongoing; Lead: NOAA; EPA]

Action 5.3.3. Develop clear, concise materials to communicate the outcomes of socio-cultural and economic risk assessments or adaptation strategies [New]

Widespread and accessible descriptions of anticipated impacts and the resources available to adapt to changing conditions will increase public awareness. Multiple materials suited to the audience will help with accessibility and relevance. For example, Tribal materials developed in collaboration with Tribal partners that includes Tribally focused impacts (e.g., culturally-significant species, impacts on cultural practices and livelihoods) can help communicate the important and relevant stakes that OA poses to cultural heritage and social and economic well-being. [Ongoing; Lead: NOAA; EPA]

Action 5.3.4. Assess the efficacy of local adaptation strategies [New]

Almost every action taken to adapt to OA will be groundbreaking, as OA is a newly recognized phenomenon that management systems have little experience with and because of expected non-stationarity in the rate of acidification and potentially its ecosystem impacts. Sound management requires investment in efforts to assess whether implemented adaptation strategies have their intended consequences and to refine or change strategies, if necessary. [Ongoing; Lead: NOAA; EPA]

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

Federal efforts to inform the public and stakeholders have expanded in conjunction with the understanding of OA and its impacts. With the recognition that education, outreach, and engagement are vital to informing affected stakeholders about OA, a variety of approaches and tools have been used, evolving with stakeholder and audience needs. National education needs-assessments have informed implementation plans to coordinate and advance education and outreach efforts among federal programs. Specifically, surveys have identified the need for more local-level information, hands-on materials, and information on solutions to enhance education efforts in schools and informal education settings. Federal agencies are working to develop a range of educational resources and tools to communicate OA science, impacts, adaptations, and solutions, and to improve communication practices about this complex subject. Federal agencies engage with ocean and coastal acidification networks in various U.S. regions, states, territories, and Tribes working to understand OA impacts specific to ecosystems, societies, and economies. In order to contribute to the advancement and sustainability of the science and engineering workforce, agencies also support the training of undergraduate and graduate students in OA research methodologies and technology developments. In all of these efforts is an intention to engage with and support underserved communities and advance equity with respect to race, ethnicity, religion, income, geography, gender identity, sexual orientation, and disability.

Objective 6.1: Develop the U.S. public's awareness of ocean acidification and its implications, and foster organizations that coordinate and lead science strategy and translation efforts in the public sector

OA has the potential to reorganize marine ecosystems, changing resource availability in ways that influence human societies and economies. Successful adaptation to, and mitigation of, the impacts of OA requires 1) robust outreach efforts to inform stakeholders about OA and its implications and 2) organizations that can lead public efforts related to OA science strategy and translation. Outreach should also include dialogues with people who are not aware of acidification or do not yet have information to understand how it may impact them personally. Such activities underlie and support action related to OA at the local and regional level by government, industry, education institutions, and non-governmental organizations.

Action 6.1.1. Encourage and support public-sector and non-profit organizations working to increase awareness of ocean acidification and to organize activities related to ocean acidification science strategy and translation [New]

OA is still a relatively new phenomenon with little public awareness and limited action in terms of management and policy. Organizations focused on OA, like the regional Coastal Acidification Networks that have formed around the United States, and those with more general missions related to coastal environments and communities, like National Estuary Programs and Sea Grant offices, can play important roles in demonstrating that the global phenomenon of OA is locally and regionally relevant. By coordinating people and their collective efforts, such organizations can catalyze actions that improve understanding of OA, what it means for local and regional resources and communities, and appropriate societal responses, including mitigation and adaptation options. [Ongoing; Lead: NOAA; EPA, NSF, USGS]

Action 6.1.2. Continue to support and engage with the Ocean Acidification Information Exchange in its role as a community of practice related to ocean acidification [Revised from 2014 Plan]

In 2018, an online website called the Ocean Acidification Information Exchange (https://www.oainfoexchange.org/) launched to meet the requirement of the FOARAM Act of 2009 to "make information on ocean acidification developed through or utilized by the interagency ocean acidification program accessible through electronic means, including information which would be useful to policymakers, researchers, and other stakeholders in mitigating or adapting to the impacts of ocean acidification." The website has been embraced by the OA community nationally and internationally, serving as an information clearinghouse and conversation/collaboration space. Supporting the Ocean Acidification Information Exchange's maintenance, development, and utilization into the future upholds a Congressional requirement and meets a need of OA researchers and stakeholders. [Ongoing; Lead: NOAA; BOEM, EPA, NPS, SI, USGS]

Action 6.1.3. Encourage federal involvement in outreach efforts related to ocean acidification [Revised from 2014 Plan]

Federal professionals representing numerous entities have emerged as leaders on OA regionally, nationally, and internationally, and serve as excellent resources for information, ideas, and innovation. Continuing robust federal engagement in OA outreach is a service to the nation and an important responsibility. Examples include federal engagement with coastal acidification networks and state efforts to respond to OA, informing citizens about OA, and supporting federally funded OA research. [Ongoing; Lead: NOAA; EPA, NSF, USGS]

Action 6.1.4. Maintain U.S. support of the Ocean Acidification International Coordination Centre [New]

Support for the OA International Coordination Centre promotes international collaboration and coordination on OA by providing access to data and resources, developing standardized methodology and best practices, raising awareness among various stakeholders, and training the next generation of scientists. To achieve these goals, the OA International Coordination Centre works with many international partners and supports global and regional OA networks, including the GOA-ON. [Ongoing; Lead: DOS; NOAA]

Action 6.1.5. Continue support of OA-related international capacity building for scientists and managers [New]

Public-private partnerships work to increase worldwide coverage of the GOA-ON, while also providing support for data collection and sensor maintenance through workshops, training, and the acquisition and deployment of sensors. Capacity-building efforts add scientists and countries to the GOA-ON, create international networks of scientists studying OA, help develop standardized protocols for OA data collection and sharing, test tools for mitigating the effects of OA through the piloting of blue carbon restoration projects, deliver kits for ocean chemistry monitoring, support the development of monitoring plans, and create an e-learning space for kit recipients through the Ocean Acidification Information Exchange. [Ongoing; Lead: DOS; NOAA]

Objective 6.2: Advance resources and opportunities related to ocean acidification at all levels of education

Sound and robust U.S. consideration of and response to OA relies on education as the foundation for development of a scientifically literate and informed public and a trained workforce who can advance and communicate about this complex topic.

Action 6.2.1. Invest in the development and coordination of ocean acidification-focused curricula and educational resources [New]

OA science is interdisciplinary, ranging from chemistry to ecology. This breadth provides opportunity in an educational setting to tie basic concepts to a real-world issue and challenges in developing lessons and curricula that do not overwhelm students with new concepts and terminology. Numerous excellent curricula and educational resources have already been developed, though the need to update them and create new ones as OA science and education theory progresses will remain. Federal support of and engagement in these efforts can help achieve excellence and coordination. [Ongoing; Lead: NOAA]

Action 6.2.2. Develop the technical workforce that can address ocean acidification by providing meaningful educational experiences [New]

The threat to resources and society from OA will grow as oceans continue to acidify and the rate of acidification increases. A highly trained workforce that can develop enhanced understanding and the tools and technology to do so is needed to meet this threat. Linking federal activities on OA with the professional development of students and early-scientists, engineers, and managers working on OA will provide meaningful experiences that enhance the U.S. workforce. [Ongoing; Lead: NOAA; EPA, NSF]

Theme 7. Data Management, Integration, and Synthesis

The success of the national OA enterprise depends critically on effective data management and integration. Data must be shared and integrated across organizational boundaries, synthesizing across diverse data management systems that were created to address distinct mission goals. Finally, data must be shared and integrated across data management technology boundaries that currently limit the interoperability between *in situ* and laboratory experiments and observations, gridded fields such as satellite products, data synthesis products, and numerical model outputs. The strategy for data management must fit within the context of national data policies and existing programs. It must follow the guidelines of the National Ocean Policy (2018, Executive Order 13840), which maintains and enhances the national benefits of the ocean, coastal, and Great Lakes waters through improved public access to marine data and information, efficient interagency coordination on ocean-related matters, and engagement with marine industries, the science and technology community, and other ocean stakeholders. Additionally, Section 10646 of the CHIPS and Science Act of 2022 modified the FOARAM Act to direct NOAA, in coordination with the IWG-OA, to support long-term access to OA data through a publicly accessible data archive system that provides OA data from a wide range of sources to the extent possible. The following actions will be pursued with these new requirements in mind.

Tremendous progress has been made in achieving the actions identified in the first Strategic Plan for Federal Research and Monitoring of Ocean Acidification. Successes include identifying a robust archive for OA data, developing metadata and data format guidance for OA data, establishing a rich metadata management system tailored to the OA community, and establishing data access portals for OA data. These actions set the foundation for the next phase of implementation, ensuring improved efficiencies in data sharing so that all agency OA data are findable, accessible, interoperable, and reusable.

Moving forward, the research community should 1) ensure OA data are archived in a timely manner, 2) enable integration of data across agencies, 3) make OA data open and publicly available, and 4) develop sustained data synthesis to fuel models and product development. To be effective, the budget for data management should be about 10-20% of the total cost of the interagency OA portfolio, considering both hardware and necessary expertise.[13]

Objective 7.1: Ensure ocean acidification data are archived in a timely manner at designated data centers

One of the top priorities of OA data management is to make sure the outcomes of OA research investments are properly archived and made accessible in machine-readable formats in accordance with federal law (e.g., OPEN Government Data Act of 2019 (Public Law 115-435), Federal Records Act of 1950 as amended) and regulations (e.g., Executive Order 13840; Office of Science and Technology Policy: Increasing Access to the Results of Federally Funded Scientific Research). The archival system guarantees data access until the minimum retention period required by the National Archives and Records Administration has been met. As a best practice, OA data acquired in proprietary or non-standards-based formats should be transformed to a non-proprietary or open format prior to submitting those data for archive.

Action 7.1.1. Improve and support capability of ocean acidification data centers to share data with long-term data archives for long-term preservation and access [New]

While much progress was made in developing robust guidance for OA data and metadata packages, sharing data among agencies, and ensuring data are shared in long-term archives, is still challenging. Cross-agency guidelines need to be developed for defining procedures for timely data submissions and data accessibility. The archive(s) still need to develop capabilities in long-term data archives for version controlling of data. [Medium term; Lead: NOAA; EPA, NSF, USGS]

Action 7.1.2. Develop a backend automation tool in base level data management to enable more streamlined publishing of data into archives [New]

One of the obstacles to sharing data between agencies and archives is ensuring an efficient online solution that is user-friendly, intuitive, and has the option for automated sharing of data files. An online submission system has been developed that supports a rich metadata template and uploading of data files. A backend automation tool is needed to enable data exchange and discoverability between archive centers and agencies. For routine sharing/submissions of data, including streaming observatory data, automated programs can publish a copy of the data into the archive in defined time frames. [Short term; Lead: NOAA; NSF]

Action 7.1.3 Support development and use of cross-agency rich metadata templates and controlled vocabularies to improve data discoverability [New]

Cross-agency rich metadata templates that meet the needs of the OA research community need to be further developed, leveraging the updated version of the OA metadata template that was developed by the Ocean Carbon and Acidification Data System.[14] Federal agencies further need to agree upon cross-agency controlled vocabularies for these metadata elements, such as observed variable, type of observation, platforms, institutions, etc. This will enable interoperability and discoverability of OA data from multiple agencies and/or archives. The establishment of common data standards, especially for biological OA data, will assist with standardizing files for data sharing and facilitate future synthesis efforts. U.S. efforts should be coordinated with global efforts, such as the UN Ocean Acidification Research for Sustainability (OARS) data management effort and the UN Sustainable

[13] Brett, A., J. Leape, M. Abbott, H. Sakaguchi, L. Cao, K. Chand, Y. Golbuu, T. Martin, J. Mayorga, and M. S. Myksvoll. 2020. Ocean data need a sea change to help navigate the warming world. Nature 582(7811): 181-183,

[14] Jiang, L. Q., S. A. O'Connor, K. M. Arzayus and A. R. Parsons. 2015. A metadata template for ocean acidification data. Earth System Science Data 7(1): 117-125. doi:10.5194/essd-7-117-2015

Development Goals (SDG) 14.3.1 data management effort. [Medium term; Lead: NOAA; BOEM, EPA, NSF, USGS]

Action 7.1.4 Support establishment and use of cross-agency guidelines for issuing Digital Object Identifiers (DOIs) [New]

DOIs are invaluable in allowing data to be cited and to attribute data to the provider. As DOIs become more widely used, further discussion is needed to prevent multiple digital object identifiers from being minted to a given data set, to ensure that an underlying digital object identifier link will point to a copy of the data set residing in a long-term archive while still attributing the original data provider, and to determine how to consistently mine digital object identifiers for different versions of a data set. [Medium term; Lead: NOAA; EPA, NSF, USGS]

Objective 7.2: Enable integration of ocean acidification data across agencies and disciplines through establishment of a virtual Ocean Acidification Data Management Office

Currently, each agency has their own data repositories, their own template to document metadata, and their own controlled vocabularies for discovery purposes. This makes it challenging to provide a national framework for archiving and data access.

Action 7.2.1. Identify agency representatives to comprise a virtual Ocean Acidification Data Management Office [Revised from 2014 Plan]

In order to update archival procedures, metadata and controlled vocabularies, and digital object identifiers, a virtual OA Data Management Office is needed, with representatives from each agency to oversee and coordinate the complex connections between institutions and data systems that will be contributing to the program. The NOAA/National Centers for Environmental Information shall serve as the lead agency for the virtual office, coordinating with the broader OA community through partnerships and leveraging of resources. [Short term; Lead: NOAA]

Action 7.2.2. Create an inventory of the current ocean acidification data activities at all U.S. government agencies with a goal of standardizing them [New]

OA data management activities still vary widely across agencies. An inventory of these activities is needed, including: a list of OA data centers, types of OA data packages each center holds, data volume, metadata templates used, controlled vocabularies used, data standards used, submission interface used, and data access interface used. This inventory will serve as a baseline to negotiate and implement common standards and approaches for the purpose of interagency OA interoperability. Uniform standards and protocols are needed for metadata templates, controlled vocabularies, and data files for collecting and documenting OA data. These efforts will be coordinated to the extent possible with international OA data management efforts, including Pangea, GOA-ON, and the OA International Coordination Centre. [Short term; Lead: NOAA; NSF]

Objective 7.3: Make ocean acidification data openly and publicly available through data frameworks that enable development of a unified catalog, web portals, and data visualization products

Executive Order 13840 requires agencies to improve coordination and to improve public access to marine data and information. Currently, agencies each publish OA data separately, and data are not captured in a common catalog or portal, making it difficult for users to discover and access OA data from one place. Utilizing data frameworks enables data to be accessed through machine-to-machine interactions from multiple places. Establishing data flows between data centers and long-term repositories is also key to enabling one-stop access to OA data.

Action 7.3.1. Scope approaches for unified portals, frameworks, and tools to provide improved access to and use of ocean acidification data across agencies [Revised from 2014 Plan]

OA data should be openly accessible through online interfaces. A user should be able to discover data based on observed variables, types of observation, spatial coverage, temporal coverage, and a free text box, regardless of where the data reside. Original data access links and data citation information from data providers should remain available. Agencies should aim to increase the uptake of OA data by various stakeholders, both by making data accessible and useable, and by conducting outreach to facilitate use. [Ongoing; Lead: NOAA]

Action 7.3.2. Standardize metadata, controlled vocabularies, and data formats for all data [Revised from 2014 Plan]

Where there are federated data sets, unifying them through data frameworks that enable data interoperability is needed so that users can easily discover, assess, integrate, and synthesize data sets from multiple providers. Establishing automation programs to transform metadata into the agreed-upon formats and share a copy of the metadata will maximize efficiencies in data sharing. Implementation of and mapping common controlled vocabularies to metadata files is also needed, to ensure data can be discovered through a uniform list of terms. All new OA data sets should be documented with the agreed-upon metadata, controlled vocabularies, and data formats. NOAA will engage the federal agencies for input to this process. [Ongoing; Lead: NOAA; NSF]

Action 7.3.3. Establish data flows to ensure ocean acidification data will be transferred to their designated long-term archive centers [New]

OA data with the appropriate level of quality control at the primary level should flow from numerous data centers to designated long-term repositories. It is anticipated that successful development of the automated interoperable discovery system will allow for transfer of data, with the agreed-upon metadata, controlled vocabularies, and data formats, to a long-term archive center within sixty days. NOAA/National Centers for Environmental Information shall serve as the long-term archive centers for chemical, physical, and biological OA observations, model output, and laboratory experiment OA data. Additional long-term archive centers can be identified for other types of OA data in the future, including for data from CO_2 removal research. [Ongoing; Lead: NOAA]

Objective 7.4: Invest in and enable data synthesis efforts to understand ocean acidification on regional to global scales

Data synthesis is defined as integrating data into a uniform standard that is quality controlled using standard procedures. Data synthesis plays a very important role in OA research, because many unique data sets have to be integrated and quality controlled in order to understand processes on a regional-to-global scale. In contrast to the large investment into OA observations (the United States is one of the largest contributors to global OA observations, responsible for at least one-third of all the OA observation data), relatively little resources have been put into OA synthesis efforts in the U.S. More resources need to be invested into regional-to-global OA synthesis efforts in order to turn observation-based research investments to OA products that will benefit the U.S. public. The virtual Data Management Office in objective 7.2.1 will assist with providing guidance and focus to agency synthesis efforts.

Action 7.4.1 Identify priorities for consolidated data synthesis, combining expertise from scientists and data managers [New]

Data synthesis needs to be a sustained process, incorporating an ever-growing number of data sets. The scope of OA data is also increasing, and data synthesis efforts need to include chemistry and biology, in order to support a growing portfolio of OA data products and forecasts. Agencies that specialize in sustained, operational observing and data infrastructure should also include robust, operational data synthesis. Any synthesis efforts must be backed with (a) long-term archive system for the original cruise data, and (b) long-term data access for the generated products. An operational data synthesis framework should merge the subject matter expertise from scientists in the academic community with technical data management expertise and infrastructure from national data centers. It is necessary to define the synthesis products needed. Target and convene a data synthesis workshop to develop the framework for a sustained data synthesis program and the initial data synthesis goals and priorities. [Ongoing; Lead: NOAA; EPA]

Action 7.4.2 Engage in synthesis of chemical and biological observation data in an effort to describe and explain acidification status of U.S. waters [New]

Great progress has been made integrating physical and chemical data at global scales. Examples include the Global Ocean Data Analysis Project and the Surface Ocean CO_2 Atlas. In contrast, synthesis efforts in the coastal ocean, where 90% of global fisheries yield and related aquaculture and recreational activities are located, are lacking. Unlike the open ocean, coastal oceans and estuaries often have larger spatial and temporal variability, as well as higher sensitivity to OA conditions. There is a clear need to broaden the OA synthesis scope to include biological synthesis and OA data product development at coastal and regional scales. [Ongoing; Lead: NOAA; EPA, USGS]

Action 7.4.3 Define and develop biological threshold and impact products for marine organisms [New]

The Nation needs OA products that inform understanding of how certain marine species will survive the changing ocean chemistry on a global scale. Current OA synthesis products focus on ocean chemistry, and there is a lack of biological global synthesis products. Over the last several decades, the number of published OA studies have increased dramatically, and much of the increase was from studies on physiological responses of marine organisms to OA. The rapid growth in research in this area makes it possible to create biological synthesis products related to laboratory experiment studies. New synthesis products may include a synthesis of how different marine organisms will respond to the changing water chemistry (e.g., calcium carbonate mineral saturation states, or pH) at their different respective life stages (e.g., eggs, juvenile, adults, etc.) in order to more readily asses species resilience to increasing OA. [Ongoing; Lead: NOAA]

Action 7.4.4. Provide public access to data synthesis products [New]

Data synthesis products will be made available either through existing or new OA data portals and frameworks to support research on trends, impacts, changing OA conditions, and interpretive product development by the broader scientific community. [Ongoing; Lead: NOAA; BOEM, NSF]

Federal Spending on Ocean Acidification

The FOARAM Act directs this strategic plan to outline budget requirements for federal OA research and monitoring and assessment activities to be conducted by each agency under the plan. While the IWG-OA does not have a budget, the individual agencies that comprise the working group each contribute to OA monitoring and research through their own spending. The table below details the spending of agencies from FY 2018 through FY 2022; all funding is reported in thousands of dollars. Primary spending refers to spending on projects that were directly focused on OA. Contributing spending refers to spending on projects that were not directly focused on OA, but contributed some information useful for understanding OA.

(thousands of dollars)	**FY18**	**FY18**	**FY19**	**FY19**	**FY20**	**FY20**	**FY21**	**FY21**	**FY22**	**FY22**
	Primary	**Contributing**	**Primary**	**Contributing**	**Primary**	**Contributing**	**Primary**	**Contributing**	**Primary**	**Contributing**
Department of Commerce (DOC)										
NOAA	14,776	8,910	17,385	11,900	18,019	9,327	21,491	5,765	20,656	5,230
NIST	0	0	0	0	145	0	145	0	480	0
DOC Total	14,776	8,910	17,385	11,900	18,164	9,327	21,636	5,765	21,136	5,230
Department of the Interior (DOI)										
BIA	349	0	149	0	0	0	0	0	0	0
BOEM	1,001	0	810	0	120	791	523	21	53	371
NPS	244	104	297	74	0	0	0	0	68	0
USGS	210	1,741	0	2,343	198	1,138	248	595	470	1,108
DOI total	1,804	1,845	1,256	2,417	318	1,929	771	616	591	1,478
Environmental Protection Agency	532	228	484	228	270	0	260	0	0	233
NASA	0	1,400	0	0	250	670	250	890	100	0
National Science Foundation	10,940	27,975	7,169	60,721	4,793	59,836	6,857	68,220	1,324	61,708
Smithsonian Institution	25	0	117	0	0	0	0	0	0	0
Department of State	839	0	252	0	0	0	0	0	0	0
Department of Agriculture	0	0	0	0	0	1,099	0	2,099	0	500
TOTAL OA FUNDING ($k)	28,916	40,358	26,663	75,266	23,795	72,861	29,774	77,590	23,151	69,148