



DRAFT | DELIBERATIVE | PREDECISIONAL

STRATEGIC PLAN FOR FEDERAL RESEARCH AND MONITORING OF OCEAN ACIDIFICATION

A Report by the
INTERAGENCY WORKING GROUP ON OCEAN ACIDIFICATION
SUBCOMMITTEE ON OCEAN SCIENCE AND TECHNOLOGY
COMMITTEE ON ENVIRONMENT
of the
NATIONAL SCIENCE & TECHNOLOGY COUNCIL

DATE

About the National Science and Technology Council

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

About the Office of Science and Technology Policy

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

About the Interagency Working Group on Ocean Acidification

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

About this Document

This document was developed by the IWG-OA 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.

Copyright Information

This document is a work of the United States Government and is in the public domain (see 17 U.S.C. §105). Subject to the stipulations below, it may be distributed and copied with acknowledgment to OSTP. Copyrights to graphics included in this document are reserved by the original copyright holders or their assignees and are used here under the government's license and by permission. Requests to use any images must be made to the provider identified in the image credits or to OSTP if no provider is identified. Published in the United States of America, 2022.

NATIONAL SCIENCE & TECHNOLOGY COUNCIL

Chair (Acting)

Alondra Nelson, Deputy Director for Science and Society, Performing the Duties of Director, Office of Science and Technology Policy

Executive Director (Acting)

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

COMMITTEE ON ENVIRONMENT

Co-Chairs

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

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

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

SUBCOMMITTEE ON OCEAN SCIENCE AND TECHNOLOGY

Chair

Alexandra Isern, National Science Foundation

Amanda Netburn, Office of Science and Technology Policy

Craig McLean, National Oceanic and Atmospheric Administration

Tom Drake, Office of Naval Research, Department of Defense

Staff

Stacy Aguilera-Peterson, Executive Secretary, National Science Foundation

Clea Harrelson, Executive Secretary, National Science Foundation

Max Showalter, Executive Secretary, National Oceanic and Atmospheric Administration

INTERAGENCY WORKING GROUP ON OCEAN ACIDIFICATION

Chair

Libby Jewett, National Oceanic and Atmospheric Administration

Staff

Shallin Busch, National Oceanic and Atmospheric Administration

Members

DRAFT | DELIBERATIVE | PREDECISIONAL

Krisa Arzayus, National Oceanic and Atmospheric Administration

Adam Bloomquist, Department of State

Rodney Cluck, Bureau of Ocean Energy Management

Eva DiDonato, National Park Service

Henrietta Edmonds, National Science Foundation

Wayne Estabrooks, United States Navy

Richard Feely, National Oceanic and Atmospheric Administration

Holly Galavotti, Environmental Protection Agency

Steve Gittings, National Oceanic and Atmospheric Administration

John Haines, United States Geological Survey

Whitman Miller, Smithsonian Institution

Ben Petro, Office of the Secretary of Defense

Deborah Rocque, United States Fish and Wildlife Service

Jennifer Arrigo, Department of Energy

Krisa Arzayus, National Oceanic and Atmospheric Administration

Shallin Busch, National Oceanic and Atmospheric Administration

Alicia Cheripka, National Oceanic and Atmospheric Administration

Adam Bloomquist, Department of State

Paula Bontempi, National Aeronautics and Space Administration

Maureen Brooks, United States Navy

Cheryl Brown, Environmental Protection Agency

Jennifer Bucatari, Bureau of Ocean Energy Management

Eva DiDonato, National Park Service

Henrietta Edmonds, National Science Foundation

Richard Feely, National Oceanic and Atmospheric Administration

Holly Galavotti, Environmental Protection Agency

Authors

Dwight Gledhill, National Oceanic and Atmospheric Administration

Jason Grear, Environmental Protection Agency

Liqing Jiang, National Oceanic and Atmospheric Administration

Libby Jewett, National Oceanic and Atmospheric Administration

Paul Knorr, Bureau of Ocean Energy Management

Pete Leary, United States Fish and Wildlife Service

Laura Lorenzoni, National Aeronautics and Space Administration

Chris Moore, Environmental Protection Agency

Whitman Miller, Smithsonian Institution

Rachael Novak, Bureau of Indian Affairs

Emily Osborne, National Oceanic and Atmospheric Administration

Kim Yates, United States Geological Survey

Table of Contents

Introduction	1
The Federal Ocean Acidification Research and Monitoring (FOARAM) Act	2
Theme 1. Research to Understand Responses to Ocean Acidification	3
<i>Objective 1.1: Develop foundational information on the sensitivity of marine organisms to ocean acidification within a multi-stressor framework</i>	3
<i>Objective 1.2: Understand the potential for marine organisms to adapt to ocean acidification in a multi-stressor framework</i>	5
<i>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</i>	6
Theme 2. Monitoring of Ocean Chemistry and Biological Impacts.....	7
<i>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 oceans</i>	7
<i>Objective 2.2: Continue global leadership in monitoring of ocean carbonate chemistry conditions and biological impacts of ocean acidification</i>	11
<i>Objective 2.3: Maintain and expand efforts to link chemical observing data to the biological impacts of OA.</i>	12
Theme 3. Improving Models of the Effects of Ocean Acidification on Ecosystems and Society	12
<i>Objective 3.1: Provide guidance for research and ocean observation efforts</i>	13
<i>Objective 3.2: Understand physical, chemical, and biological linkages related to ocean acidification</i>	13
<i>Objective 3.3: Model the linkages among ocean acidification, ecosystems, and society</i>	14
Theme 4. Technology Development and Standardization of Methods	15
<i>Objective 4.1: Develop, test, and commercialize new seawater chemistry observing technologies</i> .	15
<i>Objective 4.2: Develop and validate methods for tracking biological response to ocean acidification</i>	16
<i>Objective 4.3: Develop and validate methods for improved tracking of modern and historical changes in ocean chemistry</i>	17
<i>Objective 4.4: Foster high-quality ocean carbonate chemistry measurements by establishing community-wide quality assurance schemes and increasing availability of analytical resources</i> . .	18
<i>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 in impacted habitats</i>	19
Theme 5. Assessment of Socioeconomic Impacts and Development of Strategies to Conserve Marine Organisms and Ecosystems	20
<i>Objective 5.1: Improve understanding of sociocultural and economic risks to U.S. communities due to ocean acidification</i>	21

Objective 5.2: Use the findings of research on the biophysical and economic impacts of ocean acidification to evaluate mitigation strategies 22

Objective 5.3: Develop adaptation strategies and aid implementation 22

Theme 6. Education, Outreach, and Engagement Strategy on Ocean Acidification 23

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 23

Objective 6.2: Advance resources and opportunities related to ocean acidification at all levels of education 25

Theme 7. Data Management, Integration, and Synthesis 25

Objective 7.1: Ensure ocean acidification data are archived in a timely manner at designated data centers 26

Objective 7.2: Enable integration of ocean acidification data across agencies and disciplines through establishment of a virtual Ocean Acidification Data Management Office 27

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 28

Objective 7.4: Invest in and enable data synthesis efforts to understand ocean acidification on regional to global scales 28

Acronyms

BOEM	Bureau of Ocean Energy Management
CO ₂	carbon dioxide
DOS	United States Department of State
EPA	Environmental Protection Agency
FOARAM	Federal Ocean Acidification Research and Monitoring Act of 2009
FWS	United States Fish and Wildlife Service
FY	fiscal year
IWG-OA	Interagency Working Group on Ocean Acidification
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
NSF	National Science Foundation
NSTC	National Science and Technology Council
OA	ocean acidification
OSTP	Office of Science and Technology Policy
pCO ₂	partial pressure of carbon dioxide
ppm	parts per million
SOST	Subcommittee on Ocean Science and Technology
USGS	United States Geological Survey

1 **Introduction**

2 Since the beginning of the industrial era, fossil fuel consumption and land use changes have caused
3 global atmospheric carbon dioxide (CO₂) concentrations to rise from 280 parts per million (ppm) to
4 more than 400 ppm. This rate of CO₂ increase in the atmosphere is likely faster than at any other time
5 over the last 55 million years.¹ Anthropogenic CO₂ emissions impact the planet in ways that threaten
6 food security, national security, human health, and livelihoods. While ninety percent of the extra heat
7 from global climate change is stored in the ocean, much of the CO₂ itself is absorbed in ocean waters,
8 altering ocean chemistry. As CO₂ dissolves in water, it creates carbonic acid, causing the waters to
9 become more acidic. Ocean acidification (OA) is defined as a decrease in the pH (a measure of how
10 acidic/basic water is) of the ocean over an extended period, typically decades or longer, which is
11 caused primarily by uptake of CO₂ from the atmosphere. Anthropogenic OA refers to how much pH
12 reduction is caused by human activity. The oceans have absorbed approximately a quarter of the total
13 emitted anthropogenic CO₂, which has caused an estimated reduction in global mean surface ocean
14 pH of 0.1 unit.²

15 Most anthropogenic CO₂ emissions are derived from burning of fossil fuels (oil, gas, and coal).³ The
16 remainder are from land use changes (deforestation) and industrial processes such as cement
17 production. Additionally, freshwater inputs, ocean upwelling, nutrient runoff from land, and coastal
18 atmospheric pollution result in processes that release or deliver CO₂, acidic nitrogen, or acidic sulfur
19 compounds as byproducts into oceans, estuaries, and other bodies of water. The contribution of these
20 secondary sources vary by location. Coastal regions associated with ocean upwelling systems such
21 as the West Coast of the U.S. are especially vulnerable to OA. Coastal acidification is defined as the pH
22 decline resulting from atmospheric CO₂ combined with coastal inputs of CO₂ and other acidifying
23 compounds derived from freshwater sources, nutrient input, upwelling, and local atmospheric
24 pollution.

25 OA can be detrimental to marine life and in turn to communities that depend on the ocean for food,
26 livelihoods, and security. For example, coral reefs deteriorating in higher acidic water means less
27 protection for coastal communities from hazards such as storm surge or tsunamis. Ocean
28 acidification also threatens culturally and economically valuable fisheries such as oysters, mussels,
29 lobster, and salmon which provide protein and livelihoods to millions of people. New scientific
30 insights, methodologies and tools, and partnerships to elucidate ocean acidification trends, impacts,
31 and solutions are vital to mitigate and adapt to climate-induced ocean changes.

32 Over the past two decades, climate change research, laboratory experiments, ocean observations,
33 and examinations of the geologic record have built an understanding of how the changes in ocean
34 carbonate chemistry caused by OA have already affected marine ecosystems and may further
35 influence them in the future. Studies of the geological record suggest that extinction events co-occur
36 with OA events. Research has shown that groups of organisms, like planktonic foraminifera, have
37 already been impacted by the acidification that has occurred since the industrial revolution.
38 Laboratory experiments on species from diverse groups including shellfish, finfish, corals, and algae
39 show that some organisms are sensitive to acidified conditions. While many primary producers are
40 fertilized by extra CO₂, studies have shown how some calcium-carbonate-forming species (calcifiers)
41 experience energetic stress when building and maintaining their shells or skeletons, and some
42 crustacean and finfish species experience developmental, physiological, and behavioral issues due to
43 disruption of acid-base regulation. Observations of species in naturally more acidic areas, such as
44 areas of seawater upwelling or volcanic CO₂ vent sites, show impacts to species (i.e., shell structure,

¹ 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.

² Gruber, N., et al. (2019). The oceanic sink for anthropogenic CO₂ 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.

³ 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>

1 molecular markers of stress) and to ecosystems. Often higher acidic areas have less taxonomic
2 diversity and are dominated by fleshy algal species rather than calcifiers (e.g., shellfish, crustaceans,
3 sea urchins, etc.).

4 OA is further exacerbated by compounding factors such as increasing ocean temperatures and ocean
5 deoxygenation (the decrease in dissolved oxygen which is necessary to support organisms' basic
6 respiration). For example, higher sea surface temperatures can enhance stratification, meaning that
7 absorbed CO₂ cannot mix into deeper waters. While warmer temperatures can speed up OA, cold
8 temperatures facilitate high concentrations of dissolved CO₂. Polar waters are especially vulnerable
9 to the effects of OA because cold water can absorb more dissolved CO₂. Areas such as the Arctic face
10 more rapid acidification than other ocean basins in addition to more rapid climate-induced changes.

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

22 **The Federal Ocean Acidification Research and Monitoring (FOARAM) Act**

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

34 The FOARAM Act explicitly calls for developing a strategic research plan to guide “Federal research
35 and monitoring on ocean acidification that will provide for an assessment of the impacts of ocean
36 acidification on marine organisms and marine ecosystems and the development of adaption and
37 mitigation strategies to conserve marine organisms and marine ecosystems” (33 U.S.C. § 3704). The
38 NSTC published the first Strategic Plan for Federal Research and Monitoring of Ocean Acidification
39 in 2014. The present document serves as the required 5-year update and revision to this 2014
40 document and meets the expanded scope of the document required by the Coordinated Ocean
41 Observations and Research Act of 2020. The 2014 Strategic Plan and this new Strategic Plan focus on
42 the seven priority themes identified in the FOARAM Act: (1) research; (2) monitoring; (3) modeling;
43 (4) technology development; (5) socioeconomic impacts; (6) education, outreach, and engagement
44 strategies; and (7) data management and integration. The new Strategic Plan is organized around
45 these themes in the order in which they are presented in the FOARAM Act and consistent with
46 previous FOARAM deliverables. The plan details multiple objectives under each theme as well as
47 actions to support the objectives. Not all priorities in the 2014 Strategic Plan are retained in this
48 document however. The shift between the two Strategic Plans represents refinement of OA science,

1 better incorporation of some fields of work (i.e., social sciences, remote sensing), and
2 acknowledgement of current scientific and bureaucratic priorities. Many of the objectives and actions
3 listed in this Strategic Plan are interconnected, reflecting the interdisciplinary nature of OA research
4 and Federal OA activities. Each action indicates whether it is new, revised, or the same as the action
5 in the 2014 Strategic Plan. Each action includes a desired timeline for completion, defined as follows:
6 *short term* less than two years, *medium term* two to five years, *long term* five to ten years, and
7 *ongoing* if expected to be continual or repeated over time horizon of this Plan. Each action includes a
8 list of relevant agencies, with the recommended lead agency listed first, but does not prescribe a
9 specific approach. These lists of relevant agencies are not meant to be exhaustive or limiting.
10 Participation by additional agencies not listed will benefit many actions.

11

12 **Theme 1. Research to Understand Responses to Ocean Acidification**

13 Over the past decade, research efforts have built considerable understanding of how marine species
14 populations, ecosystems, and biogeochemical processes respond to OA alone and acting in a multi-
15 stressor framework (which includes climate change, warming, sea level rise, increased hypoxia, and
16 other anthropogenic influences). This accumulation of new research has contributed to a deeper and
17 more nuanced understanding of OA. While new research has shed light on both emergent patterns
18 and unanticipated results, it remains clear that OA has the potential to threaten whole marine
19 ecosystems and the services they provide. Sound science is required to inform the development of
20 effective mitigation strategies to build the resilience of economically important organisms, key
21 marine ecosystems and habitats, and the communities that rely on them.

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

32 *Objective 1.1: Develop foundational information on the sensitivity of marine organisms to* 33 *ocean acidification within a multi-stressor framework*

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

42 *Action 1.1.1. Quantify changes in physiological, developmental, and molecular processes in marine* 43 *organisms [Revised from 2014 Plan]*

44 Characterizing how OA in a multi-stressor framework influences physiology, survival, reproduction,
45 and other life-history characteristics of marine species is a first step to understanding impacts to
46 marine species and, in turn, food webs. Results from this action are essential to parameterize models

1 that predict population dynamics (Actions 1.1.2, 1.3.1, 3.1.2, 3.3.1). Studies designed to evaluate the
2 physiological mechanisms that underlie species' responses to OA help characterize species
3 vulnerability and will likely rely on the rapidly developing applications of genomic enabled
4 approaches (i.e., genomic, proteomic, transcriptomic, metabolomics tools collectively referred to as
5 'omics). In turn, 'omics results could be developed as reliable biomarkers of OA influence and stress
6 on marine populations (Action 1.3.1), enable the development of new biological sensors (discussed
7 under Theme 4), and better integrate monitoring of ocean biology into existing observing systems
8 (Theme 2). [Ongoing; Leads: NOAA and NSF]

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

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

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

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

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

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

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

45 *In situ* studies explore the effects of OA on organisms, communities, and ecosystems replete with
46 interactions of a naturally biodiverse system which cannot be replicated in the laboratory.
47 Experimental design for observational studies and manipulative field experiments is detailed in

1 Riebesell et al., 2010.⁴ Further effort is needed to identify new natural analog environments (both
2 future and pre-industrial) encompassing a broader range of habitats that exhibit greater chemical
3 stability and allow for better replication of experiments. Field experiments should address
4 hypotheses derived from ecological theory; greater inferential power can be achieved by coupling
5 field and laboratory studies. Studies should ensure both the carbonate system and confounding
6 factors (e.g., light, O₂, nutrients, H₂S) are adequately characterized throughout the duration of the
7 study. [Ongoing; Lead: NOAA; EPA, NSF]

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

10 Marine life has existed in oceans under conditions that are chemically different than today. However,
11 the current rates of acidification and climate change are extremely rapid in comparison to
12 environmental change during other periods in modern geological history. Furthermore, as OA
13 progresses carbonate chemistry alterations are expected to increase, exposing organisms to extreme
14 conditions that may be unprecedented, in combination with mounting anthropogenic stressors.
15 Scientists are concerned about whether the species that make up Earth's marine biodiversity have
16 the biological and/or evolutionary capacity to keep pace with the rapid changes in ocean
17 environments. Studies designed to identify and quantify species capacity for acclimation (i.e.,
18 recovery of function by individuals with prolonged exposure), as well as adaptation (i.e., genetic and
19 epigenetic changes within a population or across populations) are paramount to long-term
20 predictions about the viability of species populations and marine ecosystems, including those that
21 are viewed as both ecologically and socio-economically critical (Themes 3 and 5). Some recent
22 research provides optimism: for example, we now understand that epigenetic influences may allow
23 organisms to change more rapidly than we once thought.

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

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

34 *Action 1.2.2. Build mechanistic understanding of why organisms respond differently [Revised from*
35 *2014 Plan]*

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

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

⁴ 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.

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

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

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

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

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

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

33 The global ocean has experienced OA events in geological history that may serve as analogues for
34 present global OA and provide an improved understanding of climate feedbacks and system
35 response. Paleo studies also have the potential to quantify the progression of OA since the Industrial
36 Revolution and prior to the initiation of wide-spread observations of ocean carbonate chemistry
37 (1980s), thereby closing the gap on the incomplete observational time-series. [Ongoing; Leads: NSF
38 and USGS; NOAA, EPA]

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

42 A great deal of OA research has focused on its impacts on the formation and dissolution of calcium
43 carbonate minerals that are produced by numerous marine organisms including corals, bivalves, and
44 plankton. Calcium carbonate minerals, sediments, and structures are typically biogenic in origin and
45 define underwater topography in many regions, such as reefs. Recent research shows these features
46 are changing rapidly in some ecosystems, potentially due, in part, to OA. Additionally, efforts to infer

1 ecosystem processes from estimates of dissolution and calcification are promising. Formation and
2 weathering of calcium carbonate minerals play an important role in regulating atmospheric CO₂ on
3 geological time scales, so knowledge about these rates informs both hindcasting and forecasting of
4 the evolutionary and adaptive potential of Earth's biota. [Ongoing; Lead: NSF; NOAA, USGS]

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

7 CO₂ incorporated by phytoplankton in surface waters is consumed and metabolized through actions
8 of the pelagic food web. During this process carbon may be transferred to depth in the oceans by
9 various biological processes referred to as the "biological pump". This and other aspects of the carbon
10 cycle are coupled with other biogeochemical cycles, particularly oxygen and nitrogen cycling.
11 Understanding the actions of the biological pump and coupled biogeochemical cycles is particularly
12 relevant to understanding whether ocean regions are sources or sinks for atmospheric CO₂, whether
13 areas of low oxygen and low pH are increasing in subsurface waters, and how OA will affect marine
14 ecosystems and living marine resources. OA may influence the efficacy of the biological components
15 of the oceanic carbon cycle to remove CO₂ from the atmosphere and sequester it in the ocean long-
16 term. [Ongoing; Leads: NOAA and NSF; NASA]

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

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

25

26 **Theme 2. Monitoring of Ocean Chemistry and Biological Impacts**

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

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

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

42 On the national scale, several agencies conduct ocean and coastal acidification monitoring. A
43 description of existing observing systems is shown in the box below. For example, NOAA's Ocean
44 Acidification Program's monitoring network includes repeat hydrographic surveys, ship-based

- 1 surface observations, and time series stations (mooring and ship-based) in the Atlantic, Pacific, and
2 Arctic Oceans,⁵ and the Gulf of Mexico.

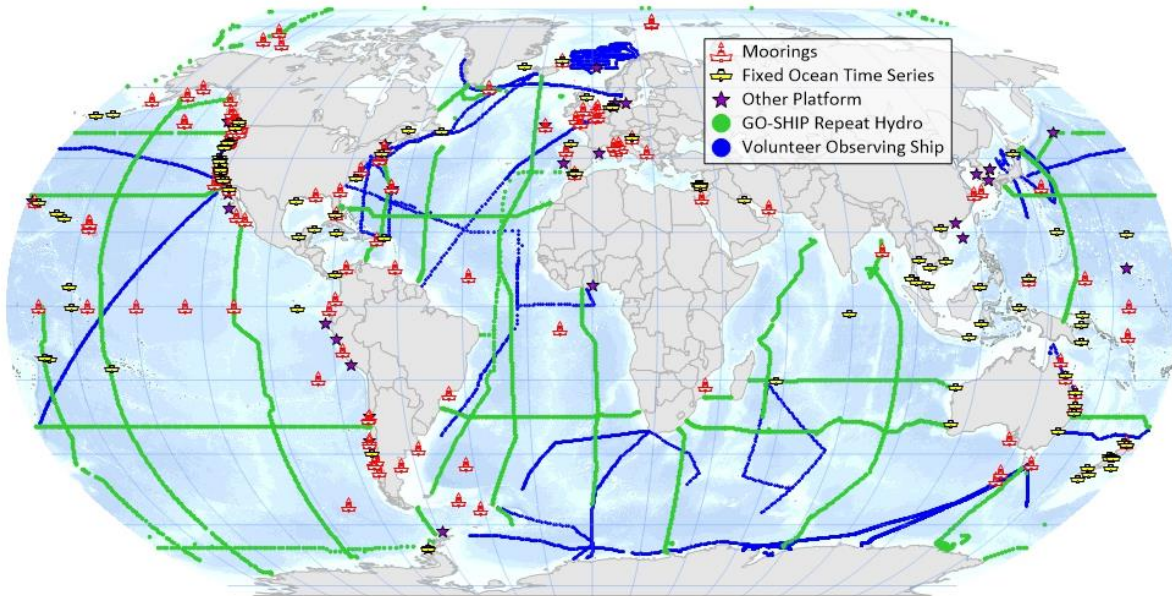
Examples of existing, major national observing programs that collect time-series ocean and coastal acidification measurements at fixed stations

- NOAA 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 US, as well as global assets elsewhere in the world’s oceans, 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 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 is comprised of 14 marine protected areas. NMSP monitoring activities are comprised of efforts targeting individual and multiple sites, including the System-Wide Monitoring Program.
- 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.

3

⁵ 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.

1 On the global scale, the Global OA Observing Network is a long-term observing network dedicated to
 2 monitor OA, understand its biological effects, and support forecasts allowing for adaptation to OA
 3 (Figure 1). The Global OA Observing Network data portal (<http://portal.goa-on.org>) serves metadata
 4 for a variety of assets, and some limited data products and visualizations of data streams.



5
 6 Figure 1. The Global Ocean Acidification Observing Network is collaborative with other open-ocean and coastal observing
 7 networks (after Tilbrook et al., 2019⁶).

8 Carbonate chemistry observations now can be measured routinely onboard ships and on moorings
 9 and floats in open water systems, as well as in estuarine and coastal systems. Maintaining existing
 10 assets and sharing methodologies and collected data from coordinated local, regional, and global
 11 observation networks is paramount and will further and solidify understanding of the impacts
 12 attributable to ocean and coastal acidification. Sharing this information is critical for validation of
 13 sensors, development of proxy methods, assessment of accuracies and general advancement of the
 14 equipment. The scarcity of biochemical *in situ* measurements limits our ability to quantify OA on a
 15 global scale. The limited coverage of *in situ* platforms does not resolve coastal and mesoscale
 16 features. For both *in situ* and remotely sensed biological monitoring, we recommend a strategic
 17 approach that enables direct comparison of the impacts of OA across different ecosystems including
 18 studies that address whether or not OA 1) leads to increased autotrophic production, 2) reduces
 19 heterotrophic production, 3) causes fundamental changes in community structure and biodiversity,
 20 4) changes the ratio of inorganic to organic carbon in pelagic and benthic systems, and 5) leads to
 21 altered rates of species and community adaptation.

22 *Action 2.1.1. Identify the existing chemical and biological ocean acidification observing assets and*
 23 *their technology, methods, measurement parameters, data collected and other relevant information.*
 24 *Ensure the information, including the data collected, is integrated into global data portals. Identify*

⁶ 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. Lebre, 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

1 *general barriers to maintaining observing assets and provide information, such as available national*
2 *and regional funding sources [Revised from 2014 Plan]*

3 The identification of existing assets across the agencies could be done best on a regional basis and
4 will improve the understanding of the capabilities of current observing stations, where synergies
5 could be made, gaps may exist, or where technology development is needed. Some States, Tribes, and
6 regional organizations are engaged in this monitoring and have developed or contributed to
7 inventories. For example, the regional Coastal Acidification Networks are valuable resources to
8 ensure that the agencies have a good understanding of existing assets. Several Integrated Ocean
9 Observing System Regional Associations, in partnership with NOAA's Ocean Acidification Program,
10 coordinate regional coastal acidification networks. Each network works with a variety of partners
11 such as state agencies, researchers, industry, tribal members, and concerned citizens to assess how
12 changes in ocean and coastal chemistry are manifested in the region, identify gaps, and develop
13 mitigation strategies. The West Coast states, through the West Coast Ocean Acidification Task Force,
14 have inventoried regional chemical and biological OA observing assets from California to Alaska, and
15 some states are undergoing prioritization exercises for potential new assets. [Ongoing; Leads: NOAA
16 and NSF; BOEM, EPA, USGS]

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

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

33 *Action 2.1.3. Expand coastal acidification monitoring in nearshore and estuarine areas. Identify and*
34 *deploy monitoring instrumentation in coastal and estuarine sites to extend the carbonate chemistry*
35 *and biological monitoring parameters for these shallow water systems [New]*

36 Quantifying the impacts of ocean and coastal acidification in estuarine habitats is complex due to the
37 many natural and human processes affecting acidification of these systems, however determining the
38 role of anthropogenic factors is essential in order to understand the spatial and temporal dynamics
39 and the regional drivers of acidification and ultimately to predict the vulnerability of these
40 ecosystems. Specifically, understanding the effects of local atmospheric inputs, riverine inflow, local
41 pollution inputs (e.g., wastewater, urban stormwater runoff), upwelling and other factors that can
42 exacerbate the effects of near-shore acidification in critical ecosystems. Additionally, while many of
43 the sensors that measure carbonate chemistry parameters have been used extensively in the open
44 ocean, their use in the estuarine environment is novel and challenging due to biofouling, tidal
45 influence, seasonal and diel variability and other factors and will benefit from technology
46 development and standardization (Theme 4). Further expanding acidification monitoring in near-
47 shore and estuarine areas will help fill the existing knowledge gap and push the current technology
48 to perform in such a challenging environment. Evaluating the efficacy and impacts of methods for

1 sequestering carbon in nearshore environments, such as alkanization of power plant effluent and
2 enhancing submerged aquatic vegetation, will require expansion of carbonate chemistry monitoring
3 efforts. [Ongoing; Lead: EPA; NOAA, NPS, USGS]

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

7 Based on the prioritization in Action 2.1.2, OA monitoring will need to be expanded to high-latitude
8 regions, upwelling regions, warm and cold-water coral reefs, the full water column and other areas
9 where less is understood about the temporal and spatial variability of acidification. It will be
10 important to evaluate existing national monitoring networks and identify opportunities to deploy
11 new OA monitoring instrumentation on research ships, volunteer observing ships, moorings, and
12 autonomous floats and gliders (Theme 4). Supporting efforts related to CO₂ removal, such as
13 enhancement of primary productivity, from the atmosphere to long-term sequestration in the open
14 ocean will require expansion of the carbon chemistry monitoring network to track changes in
15 acidification. [Ongoing; Lead: NOAA; BOEM, EPA, NSF, USGS]

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

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

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

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

37 The Global OA Observing Network should also provide support for capacity building through
38 workshops, training, and the acquisition and deployment of sensors. Capacity-building efforts add
39 new scientists and new countries to the Global OA Observing Network, create new international
40 networks of scientists studying OA, help develop standardized protocols for OA data collection and
41 sharing, integrate new protocols for autonomous sensors on moorings, floats and gliders, test tools
42 for mitigating the effects of OA through the piloting of blue carbon restoration projects, deliver kits
43 for ocean chemistry monitoring, support the development of monitoring plans, and create an e-
44 learning space for kit recipients through the Ocean Acidification Information Exchange.

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

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

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

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

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

28 *Action 2.3.1. Continue to foster closer connections between scientists to provide pertinent*
29 *information about carbon chemistry of waters where species being studied reside naturally [From*
30 *2014 Plan]*

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

35
36 **Theme 3. Improving Models of the Effects of Ocean Acidification on Ecosystems and Society**

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

45 Modeling efforts that permit exploration of species adaptation capacity and account for species
46 behavior can be used to characterize organism and ecosystem response to OA and evaluate
47 management strategies in an acidified ocean. There are significant scaling issues that complicate

1 linkage of biogeochemistry ocean general circulation models with finer scale ecological organization
2 and high spatiotemporal heterogeneity of coastal environments. Solutions to these scaling problems
3 will both inform and depend upon results from observation programs and biological/ecological
4 studies (Themes 1 & 2). Ultimately, these issues are not specific to ocean modeling, but to all attempts
5 to identify and capture appropriate scales of ecosystem complexity in a computer model and then
6 project how the system will respond.

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

20 *Objective 3.1: Provide guidance for research and ocean observation efforts*

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

24 *Action 3.1.1. Explore the use of Observing System Simulation Experiments to optimize in situ and* 25 *remote sensing ocean acidification observation network design [Revised from 2014 Plan]*

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

29 *Action 3.1.2. Facilitate communication between modelers, field and lab researchers to improve model* 30 *predictive capability [New]*

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

36 *Objective 3.2: Understand physical, chemical, and biological linkages related to ocean* 37 *acidification*

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

43 *Action 3.2.1. Invest in and develop multi- and interdisciplinary models to ensure coupling of coastal* 44 *processes on both sides of the land-ocean boundary, as well as atmospheric and benthic processes* 45 *[Revised from 2014 Plan]*

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

7 *Action 3.2.2. Continue progress implementing key carbonate system tracers and processes in*
8 *BOGCMs, such as alkalinity, PIC, and dissolution [Revised from 2014 Plan]*

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

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

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

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

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

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

34 Ecosystem models, coupled to biogeochemical and hydrodynamic models, are an important tool for
35 forecasting the impact of OA on society. OA is expected to alter ocean chemistry and affect marine
36 resources in ways that will likely cause current management practices to fail to meet their objectives
37 and impede success of fisheries and coastal recreation industries. Incorporating knowledge on
38 species and ecosystem response to OA – including knowledge about whether these responses
39 combine additively or synergistically with other stressors – into economic and resource management
40 to guide management decisions will benefit the communities, industries, and economies that rely on
41 marine resources. [Ongoing; Lead: NOAA; BOEM, EPA, USGS]

42 *Action 3.3.2. Develop and improve linkages between ecosystem models and economic models [New]*

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

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

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

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

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

14

15 **Theme 4. Technology Development and Standardization of Methods**

16 As with any scientific program, ensuring adequate data quality of measured parameters is critical for
17 OA research, which is transdisciplinary, with many chemical, biological, and physical characteristics
18 that need to be concurrently monitored. Effective OA monitoring and research has benefited from
19 advanced technology and methodological development in recent years including best practices,
20 refined quality control protocols, and new sensor technologies. However, considerable needs remain
21 in each of these areas including achieving affordable, adaptable, and robust instrumentation for
22 continuous autonomous monitoring of OA both in the field and laboratory that can fully characterize
23 changes unfolding within coastal, ocean and freshwater environments at frequencies, depths, and
24 scales most relevant to biological processes to better inform numerical models. Specifically,
25 approaches are needed to better characterize habitats most relevant to species and life-stages
26 demonstrated to be sensitive to OA, including below the mixed layer depth, at the sediment-water
27 interface, and in environments influenced by freshwater. Improved capabilities are needed to detect
28 biologically meaningful response effects; better avoid type-I and type-II errors, and to achieve
29 appropriate replication for statistically sound conclusions. Other focus areas include ensuring:
30 appropriate, comparable and standardized methods are further developed; suitable measurement
31 approaches are adopted where uncertainties are quantified and fit-to-purpose; sensor and other
32 technologies are strategically developed to maximize data quality, coverage and cost effectiveness;
33 and centers of technical expertise and/or shared community research facilities are maintained and
34 broadly accessible. Finally, remotely sensed data remains underutilized in its ability to infer OA high-
35 frequency dynamics or map secular changes in habitat response and represents an area of potential
36 growth in coming years.

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

39 Methods and technologies have been developed for discrete and autonomous inorganic carbon
40 measurements from seawater. However, use of autonomous instruments remains costly (except for
41 a few parameters) and remains unavailable from commercial suppliers and/or unreliable for
42 sustained deployments. Monitoring technology using unmanned platforms has been developed,
43 including moorings, gliders, autonomous vehicles, floats, and satellites. However, continued efforts
44 need to focus on development of highly reliable, easy to use, low-power, inexpensive, robust,
45 adaptable, commercial analytical systems for these platforms that include the full suite of carbon
46 system and supporting chemical variables.

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

4 Progress has been made on development of pH and pCO₂ sensors, but continued research,
5 development and testing are still needed. In addition, new attention should focus on dissolved
6 inorganic carbon and total alkalinity sensors to improve versatility for use in coastal/estuarine
7 systems which have highly variable chemistry, and inclusion of better anti-biofouling capacity for
8 field deployments. The NOAA Alliance for Coastal Technologies program should be engaged in
9 evaluation of these new sensor technologies. Development of an additional carbon sensor
10 appropriate for deployment on surface gliders, biogeochemical Argo floats and profiling gliders
11 should be encouraged. Federal agencies should seek to expedite the transition of all these
12 technologies to commercialization through stronger partnerships with private industry, using
13 mechanisms including the National Oceanographic Partnership Program, agency Small Business
14 Innovation Research funding, and NSF's Oceanographic Technology and Interdisciplinary
15 Coordination program. [Ongoing; Leads: NOAA and NSF; EPA, USGS]

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

19 Subsurface water column, deep and cold-water deployments have been particularly challenging and
20 require special attention. Depth requirements range from near the surface (few meters) to deep
21 (60+ meters). Performance; analytical capabilities; and science-quality real-time data reporting of
22 gliders, autonomous underwater vehicles, drifters, profilers, moorings need to be improved to
23 accommodate these challenging environments. The international effort to develop and expand
24 biogeochemical Argo float monitoring to include OA measurement requirements should be
25 supported. [Ongoing; Leads: NOAA and NSF]

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

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

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

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

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

43 Recent advances have allowed for an extension of the biogeochemical Argo program to begin
44 adopting biogeochemical observations (oxygen, nitrate, pH, chlorophyll, etc.) that will permit a
45 valuable means of linking OA to large-scale changes in global ocean biogeochemical processes which
46 may be altered by or interact with OA. Various sensors have now been demonstrated on a range of

1 platforms (e.g., gliders, moorings). Inclusion of rapid, cost-effective technologies for quantifying
2 abundances of targeted organisms affected by OA remains elusive and should be sought for inclusion
3 in integrated OA observation networks (e.g., Global OA Observing Network). [Ongoing; Leads: NOAA
4 and NSF]

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

7 Best methods for many discrete and underway measurements of the inorganic carbon system are
8 well established and described in guides to best practices and should be followed whenever
9 possible.⁷ However, additional measurement techniques are required to improve measurements in
10 diverse coastal environments. Establishing historical context for the current anthropogenic
11 acidification event is critical to assessing its relative severity to past events and understanding how
12 marine ecosystems might be altered under continued acidification over coming decades to centuries.
13 Continued fundamental research is required to develop best practices for use of proxies for paleo-OA
14 environmental conditions and to develop methods and calibrations for measurement of additional
15 ocean chemistry parameters. Looking to the future, technology developments are needed to assess
16 how proposed approaches for removal of CO₂ from the atmosphere by sequestration in ocean
17 ecosystems affects acidification in ocean ecosystems.

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

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

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

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

39 *Action 4.3.3. Analyze technologies and methods for sequestering atmospheric carbon dioxide into*
40 *long-term storage in ocean ecosystems.*

41 Recognition is growing that removing CO₂ from the atmosphere is required to meet targets related
42 to protecting human and ecosystem welfare from the largest impacts of climate change and OA. Ocean
43 alkalinity enhancement is a leading technological solution for CO₂ removal and involves adding

⁷ Dickson, A. G., C. L. Sabine and J. R. Christian (Eds.). 2007. *Guide to best practices for ocean CO₂ 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.

1 alkaline materials to the ocean to both enhance drawdown of atmospheric CO₂ and mitigate OA.
2 Ocean alkalinity enhancement is fundamentally a manipulation of ocean carbon chemistry, so falls
3 within the purview of this OA research strategy. Before this solution could be deployed at scale
4 research is needed to test methodologies for implementing it, document its efficacy, and understand
5 and robustly communicate its implications for ocean ecosystems and natural resources. [Ongoing;
6 Lead: Currently undefined; BOEM, EPA, NOAA, USGS]

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

10 The current analytical capacities and expertise in carbon system dynamics, as it pertains to OA, are
11 not adequate in most laboratories.

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

15 As the OA research community grows, additional climate grade analytical centers, located in both
16 Federal and academic laboratories, will be needed to help make analytical services more accessible
17 and to develop expertise in OA issues unique to different regions. Continued OA short courses and
18 web series, taught by experts in the field, are needed to educate the broader community on available
19 techniques, proper analytical methods and experimental design. [Ongoing; Leads: NOAA and NSF;
20 USGS; NIST]

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

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

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

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

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

41 Continue the use of inorganic carbon certified reference materials produced at the Scripps Institution
42 of Oceanography/UC San Diego for verifying that dissolved inorganic carbon and total alkalinity
43 measurements are consistent with an agreed-upon international standard. Continue international,

1 interlaboratory calibration exercises using methods established during 2013 calibration exercises.⁸
 2 Explore development of a certification program for centers of excellence and identification of these
 3 certified centers. [Ongoing; Lead: NOAA; EPA, USGS; NIST]

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

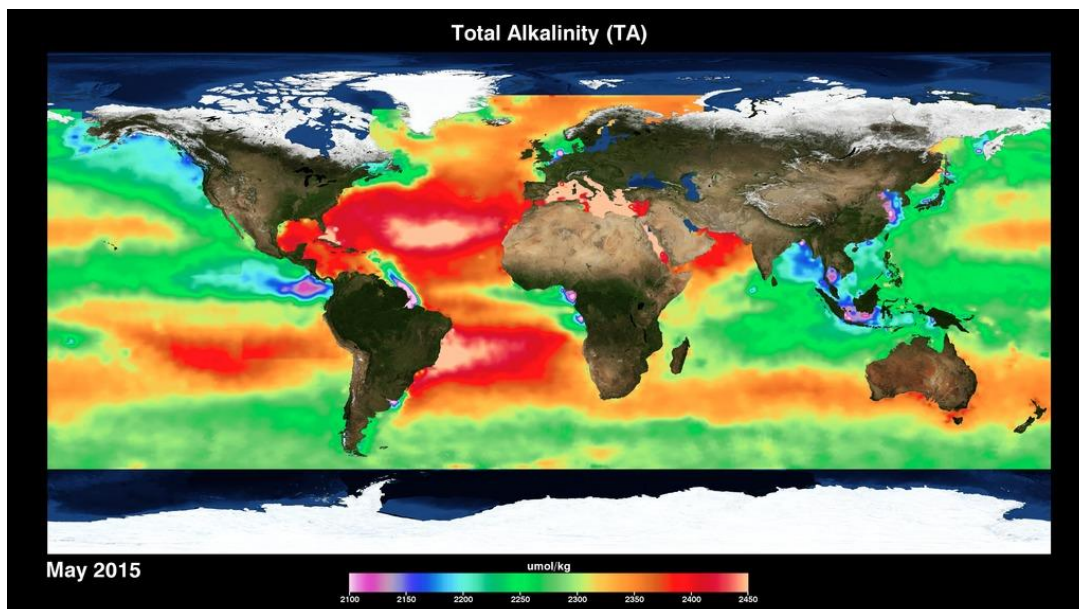
7 Remote sensing offers a powerful tool for studying surface OA dynamics. Surface physical and
 8 biological phenomena which influence carbonate system dynamics (e.g., sea surface temperature,
 9 salinity, optical properties, primary productivity) are readily available via remote sensing (Figure 2).
 10 Satellite data coupled to *in situ* observations can be applied to derive synoptic estimates of OA
 11 conditions and governing processes and support a diverse range of activities from cruise planning to
 12 model validation.

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

15 Currently, a global beta product exists that incorporates satellite sea surface height, modeled salinity,
 16 and satellite ocean color and temperature. However, case studies currently remain limited to the
 17 coastal regions as part of the U.S. Marine Biodiversity Observing Network; and methods should be
 18 developed for expansion to pelagic seascapes. [Ongoing; Leads: NASA and NOAA]

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

22 Satellite remote sensing can provide synoptic observations of a range of physical and bio-optical
 23 parameters that allow us to understand changes in the Earth at unprecedented temporal and spatial
 24 scales. Changes in the distribution of carbonate chemistry within the surface ocean can be derived



25
 26 Figure 2. Satellite surface salinity data are becoming key in monitoring ocean carbon cycle, enabling the first space-borne
 27 maps of OA. Shown here is monthly surface total alkalinity derived using Aquarius salinity. Credit: NASA

⁸ 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.

1 with remote sensing assets; this can be particularly useful in areas where no *in situ* observations are
2 available. However, the relationships between bio-optical parameters measured by satellite and *in*
3 *situ* chemistry are complex. Satellite proxies need further algorithm development to improve their
4 utility. Algorithm development can be facilitated by utilizing paired biogeochemical and *in situ*
5 optical measurements from on-going OA surveys with satellite measurements. Efforts could also be
6 taken to derive surface ocean pCO₂ at suitable spatiotemporal scales (e.g., monthly, 0.5 degree) using
7 surface ocean gridded data synthesis products (e.g., Surface Ocean CO₂ Atlas) applied to remotely
8 sensed data products to produce gridded fields of monthly global sea surface pCO₂. [Ongoing; Leads:
9 NASA and NOAA]

10

11 **Theme 5. Assessment of Socioeconomic Impacts and Development of Strategies to Conserve** 12 **Marine Organisms and Ecosystems**

13 We are just beginning to unravel the full effects of increased CO₂ in the atmosphere and the resultant
14 alterations in ocean chemistry and, therefore, are not yet able to fully understand the consequences
15 that this process will have on our society. Increasing our understanding of the effects of OA will
16 inform discussions of climate change mitigation and adaptation, thus helping stakeholders and
17 decision makers to respond more efficiently.

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

- 21 • Aquaculture – Hatcheries and grow-out facilities are dependent on careful control of the
22 environment in which their stocks are grown. For saltwater species, ocean water is often
23 pumped in and will have to be monitored and controlled to avoid mortality, increasing the
24 costs of production and/or reducing output. Currently, early life stages of some cultured
25 shellfish occur in coastal waters and may be impacted by acidification.
- 26 • Tropical Coral Reef Systems – Coral reef systems are complex and already being damaged by
27 other anthropogenic stressors like water pollution, destructive fishing practices, and climate
28 change. The addition of OA to these stressors will exacerbate adverse effects on the health of
29 corals and coralline algae. Coral reefs provide habitat for commercial and subsistence
30 fisheries, support tourism and recreation markets, provide protection from coastal flooding
31 and erosion, and contribute to marine biodiversity.
- 32 • Marine Fisheries – Commercially valuable finfish may be affected directly by acidifying
33 waters and through the food web. OA is also likely to affect critical habitat for some species,
34 such as alterations in coral and oyster reefs. Wild harvest of shellfish may have to shift to
35 aquaculture production where seawater chemistry can be monitored and controlled.
- 36 • Subsistence Shellfish Harvesting and Fisheries – Many of the marine organisms that are most
37 intensely affected by OA contribute substantially to the traditional subsistence way of life of
38 coastal indigenous populations.

39 Aggregate measures of economic impacts, such as percentage Gross Domestic Product lost due to
40 environmental damages, are useful summary statistics but tell only part of the story. It is also
41 important to examine how those impacts are distributed across the affected population. Economic
42 impacts of environmental damages can disproportionately affect some State, local, or Tribal
43 governments; geographic locations; or subpopulations of interest including historically
44 disadvantaged communities that may rely on affected species for subsistence harvesting and cultural
45 practices. While economic impact assessments are valuable tools to inform priorities, it should be

1 noted that some values cannot be accurately monetized. Decision makers will require this knowledge
2 as they craft mitigation and adaptation strategies for OA.

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

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

10 The ultimate goal of assessing the economic impacts of OA is to weigh the near-term costs of
11 mitigation and adaptation against the mounting costs of unmitigated impacts. Assessing the
12 economic impacts of OA will require several components, including long-term forecasts of
13 socioeconomic conditions, valuation of market and non-market impacts, integrated assessment
14 modeling, social discounting, and uncertainty analysis. Such an impact assessment would then permit
15 analysis of the cost-effectiveness of mitigation and adaptation strategies.

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

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

22 *Action 5.1.2. Conduct new non-market valuation and economic impact studies to estimate damages*
23 *from different impacts of ocean acidification as we come to understand them [Revised from 2014*
24 *Plan]*

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

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

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

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

38 Conduct research at the intersection of traditional knowledge from coastal Indigenous communities
39 and the coastal ecosystem science from Western science. Assessments surrounding this collaboration
40 would help to better understand change in shellfish and coastal ecosystems resources and how they
41 are affecting these communities culturally and economically. This traditional knowledge can help
42 provide a longer-term perspective from the communities who have relied on subsistence or
43 supplemental harvesting for generations. [Ongoing; Lead: NOAA]

1 *Objective 5.2: Use the findings of research on the biophysical and economic impacts of ocean*
2 *acidification to evaluate mitigation strategies*

3 The most direct way to reduce OA is to reduce the atmospheric concentration of CO₂. This requires
4 sharp reductions in CO₂ emissions, increasing CO₂ sequestration, or both. Strategies to reduce
5 greenhouse gas emissions have been extensively investigated under climate change discussions and
6 can be found in various Federal reports. They include establishment of regulatory standards on
7 emission levels, financial incentives for innovative technology development, tradable permits,
8 increasing energy efficiency, reduction of deforestation, promotion of reforestation, and shifting
9 energy sources from fossil fuels to alternative energy sources. These solutions would require an
10 organized and committed international effort that crosses social, cultural, and political boundaries.

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

14 The social cost of carbon is a measure of the economic benefit from a marginal reduction in CO₂
15 emissions and is used to evaluate the economic efficiency of regulations affecting CO₂ emissions. All
16 estimates of the social cost of carbon produced to date quantify damages from climate change but
17 omit impacts from OA. This is a potentially large omission that leads to an underestimate of the social
18 cost of carbon and the benefits from regulations that reduce CO₂ emissions. To more accurately
19 evaluate the economic efficiency of CO₂ emissions policies, OA impacts need to be included in the
20 integrated assessment models we use to estimate social cost of carbon. How those impacts are
21 distributed across political boundaries and socioeconomic groups is also important information that
22 integrated models can provide to decision makers. [Ongoing; Lead: NOAA; BOEM, EPA]

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

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

31
32 *Objective 5.3: Develop adaptation strategies and aid implementation*

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

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

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

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

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

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

9 Widespread and accessible descriptions of anticipated impacts and the resources available to adapt
10 to changing conditions will increase public awareness. Multiple materials suited to the audience will
11 help with accessibility and relevance. For example, tribal materials developed in collaboration with
12 tribal partners that includes tribally-focused impacts (e.g., culturally-significant species, impacts on
13 cultural practices and livelihoods) will be more useful than one developed for business owners.
14 [Ongoing; Lead: NOAA; EPA]

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

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

21

22

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

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

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

44 OA has the potential to reorganize marine ecosystems, changing resource availability in ways that
45 influence human societies and economies. Successful adaptation to and mitigation of the impacts of

1 OA requires 1) robust outreach efforts to inform stakeholders about OA and its implications and 2)
2 organizations that can lead public efforts related to OA science strategy and translation. Such
3 activities underlie and support action related to OA at the local and regional level by government,
4 industry, education institutions, and non-governmental organizations.

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

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

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

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

29 *Action 6.1.3. Encourage Federal involvement in outreach efforts related to ocean acidification*
30 *[Revised from 2014 Plan]*

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

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

38 Support for the OA International Coordination Centre promotes international collaboration and
39 coordination on OA by providing access to data and resources, developing standardized methodology
40 and best practices, raising awareness among various stakeholders, and training the next generation
41 of scientists studying OA. To achieve these goals, the OA International Coordination Centre works
42 with many international partners and supports global and regional OA networks, including the Global
43 Ocean Acidification Observing Network. [Ongoing; Lead: DOS; NOAA]

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

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

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

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

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

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

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

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

32

33 **Theme 7. Data Management, Integration, and Synthesis**

34 The success of the national OA enterprise depends critically on effective data management and
35 integration. Data must be shared and integrated across organizational boundaries, synthesizing
36 across diverse data management systems that were created to address distinct mission goals. Finally,
37 data must be shared and integrated across data management technology boundaries that currently
38 limit the interoperability between in situ and laboratory experiments and observations, gridded
39 fields such as satellite products, data synthesis products, and numerical model outputs. The strategy
40 for data management must fit within the context of national data policies and existing programs. It
41 must follow the guidelines of the National Ocean Policy (2018, Executive Order 13840), which
42 maintains and enhances our national benefits of the ocean, coastal, and Great Lakes waters through
43 improved public access to marine data and information, efficient interagency coordination on ocean-
44 related matters, and engagement with marine industries, the science and technology community, and
45 other ocean stakeholders.

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

8 Moving forward, the research community should 1) ensure OA data are archived in a timely manner,
9 2) enable integration of data across agencies, 3) make OA data open and publicly available, and 4)
10 develop sustained data synthesis to fuel models and product development. To be effective, the budget
11 for data management should be about 10-20% of the total cost of the interagency OA portfolio,
12 considering both hardware and necessary expertise.⁹

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

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

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

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

31 *Action 7.1.2. Develop an online submission system capable of supporting a rich metadata template*
32 *and uploading data files, and a backend automation tool in base level data management to enable*
33 *more streamlined publishing of data into archives [New]*

34 One of the obstacles to sharing data between agencies and archives is ensuring an efficient online
35 solution that is user-friendly, intuitive, and has the option for automated sharing of data files. An
36 online submission system should be further developed that includes a graphical user interface for
37 input of metadata information and uploading of data files. The backend automation tool needs to
38 enable data exchange and discoverability between archive centers and agencies. For routine
39 sharing/submissions of data, including streaming observatory data, automated programs can
40 publish a copy of the data into the archive in defined time frames. [Short term; Lead: NOAA; NSF]

41 *Action 7.1.3 Support development and use of cross-agency controlled vocabularies for metadata*
42 *elements to improve data discoverability [New]*

⁹ 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.

1 Cross-agency rich metadata templates that meet the needs of the OA research community need to be
2 further developed, leveraging the updated version of the OA metadata template that was developed
3 by the Ocean Acidification Data Stewardship Project.¹⁰ The agencies further need to agree upon
4 cross-agency controlled vocabularies for these metadata elements, such as observed variable, type
5 of observation, platforms, institutions, etc. This will enable interoperability and discoverability of OA
6 data from multiple agencies and/or archives. U.S. efforts should be coordinated with global efforts
7 through the OA-International Coordination Centre. [Medium term; Lead: NOAA; BOEM, EPA, NSF,
8 USGS]

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

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

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

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

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

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

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

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

¹⁰ 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

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

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

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

12 OA data should be openly accessible through online interfaces. A user should be able to discover data
13 based on observed variables, types of observation, spatial coverage, temporal coverage, and a free
14 text box, regardless of where the data resides. Original data access links and data citation information
15 from data providers should remain available. [Ongoing; Lead: NOAA]

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

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

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

28 OA data should flow from numerous data centers to designated long-term repositories. It is
29 anticipated that successful development of the automated interoperable discovery system will allow
30 for transfer of data, with the agreed upon metadata, controlled vocabularies, and data formats, to a
31 long-term archive center within sixty days. NOAA/National Centers for Environmental Information
32 shall serve as the long-term archive centers for chemical and laboratory experiment OA data.
33 Additional long-term archive centers can be identified for other types of OA data in the future,
34 including for data from CO₂ removal research. [Ongoing; Lead: NOAA]

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

37 Data synthesis is defined as integrating data into a uniform standard that is quality controlled using
38 standard procedures. Data synthesis plays a very important role in OA research, because many
39 unique data sets have to be integrated and quality controlled in order to understand processes on a
40 regional to global scale. In contrast to the large investment into OA observations (the U.S. is one of
41 the largest contributors to global OA observations, responsible for at least 1/3 of all the OA observation
42 data), relatively little resources have been put into OA synthesis efforts in the U.S. More resources
43 need to be invested into regional to global OA synthesis efforts, in order to turn observation-based
44 research investments to OA products that will benefit the U.S. public. The virtual Data Management
45 Office in objective 7.2.1 will assist with providing guidance and focus to agency synthesis efforts.

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

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

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

16 Great progress has been made integrating physical and chemical data at global scales. Examples
17 include the Global Ocean Data Analysis Project and the Surface Ocean CO₂ Atlas. In contrast, synthesis
18 efforts in the coastal ocean, where 90% of global fisheries yield and related aquaculture and
19 recreational activities are located, are lacking. Unlike the open ocean, coastal oceans and estuaries
20 often have larger spatial and temporal variability, as well as higher sensitivity to OA conditions. There
21 is a clear need to broaden the OA synthesis scope to include biological synthesis and to develop
22 products at coastal and regional scales to guide regional OA product and model development.
23 [Ongoing; Lead: NOAA; EPA, USGS]

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

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

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

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

40

41 **Federal Spending on Ocean Acidification**

42 PLACEHOLDER TEXT: The FOARAM Act directs this strategic plan to outline budget requirements for
43 federal ocean acidification research and monitoring and assessment activities to be conducted by
44 each agency under the plan. While the IWG-OA does not have a budget, the individual agencies that
45 comprise the working group each contribute to ocean acidification monitoring and research through

- 1 their own spending. The final version of this plan will be updated to include budget information on
- 2 federal spending on ocean acidification by agency.
- 3