Strategic Plan for Federal Research and Monitoring of Ocean Acidification

Prepared by
Interagency Working Group on Ocean Acidification
Subcommittee on Ocean Science and Technology
Committee on Environment, Natural Resources, and Sustainability
National Science and Technology Council

Report directed by Section 12404(c) and guided by Section 12405 of the Federal Ocean Acidification Research and Monitoring Act of 2009
(FOARAM Act)

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Executive Summary

Oceans provide vital resources and services for sustaining humankind, including food, recreation, transportation, energy, nutrient cycling, as well as moderating climate, and they contribute substantially to the economy. However, the chemistry of the oceans is changing in ways that will have impacts on the services and resources provided by the oceans. Several Federal agencies are working towards developing a collective approach to understand and address this rapidly emerging problem, commonly referred to as ocean acidification. Recognizing the need for a comprehensive interagency plan to address the increasing impacts of ocean acidification, Congress passed the Federal Ocean Acidification Research and Monitoring Act of 2009 (FOARAM Act), which defines ocean acidification as "the decrease in pH of the Earth's oceans and changes in ocean chemistry caused by chemical inputs from the atmosphere, including carbon dioxide." Coastal and estuarine acidification, to the extent that the cause of the acidification can be traced back to anthropogenic atmospheric inputs to the ocean, are assumed to be covered by this plan wherever ocean acidification is referenced.

The FOARAM Act calls on the Subcommittee on Ocean Science and Technology (SOST) to establish an Interagency Working Group on Ocean Acidification (IWG-OA). The Act also explicitly calls for developing a strategic research plan to guide "Federal research and monitoring on ocean acidification that will provide for an assessment of the impacts of ocean acidification on marine organisms and marine ecosystems and the development of adaption and mitigation strategies to conserve marine organisms and marine ecosystems." The IWG-OA was chartered in October 2009, and it is comprised of representatives from the National Oceanic and Atmospheric Administration (NOAA), National Science Foundation (NSF), Bureau of Ocean Energy Management (BOEM), U.S. Department of State (DOS), U.S. Environmental Protection Agency (EPA), U.S. Fish and Wildlife Service (FWS), National Aeronautics and Space Administration (NASA), U.S. Geological Survey (USGS), and the U.S. Navy. The IWG-OA is chaired by NOAA, and the vice-chair is from NSF.

In preparing this strategic research plan, the IWG-OA focused on seven priority themes identified in the FOARAM Act. The themes include the five Program Elements set forth as the minimum requirements for the plan and two elements required for successful implementation of the plan. The seven themes address: (1) monitoring, (2) research, (3) modeling, (4) technology development, (5) socioeconomic impacts, (6) education, outreach, and engagement strategies, and (7) data management and integration. These themes lay out recommendations and short-term (3- to 5-year) and long-term (10-year) goals that emphasize:

- Building upon existing systems and developing new technology and systems that monitor chemical and biological impacts of ocean acidification worldwide, document trends, and develop early warning systems.
- Undertaking laboratory, mesocosm, and *in situ* research to examine species-specific physiological responses to ocean acidification and its interactions with other stressors, impacts to marine food webs and ecosystems, and mechanisms necessary to develop indices to track marine ecosystem responses.
- Developing comprehensive models to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms.

- Ensuring the ability to measure all required parameters and adequate data quality through technology development and standardization of measurements.
- Fostering a coordinated Federal approach to technology development and standardization efforts.
- Assessing the socioeconomic impacts of ocean acidification.
- Identifying and engaging stakeholders and local communities in developing adaptation and mitigation strategies for responsible stewardship of marine organisms and ecosystems.
- Designing and coordinating activities that foster ocean acidification literacy through educational resources and public outreach.
- Developing and implementing domestic and international engagement strategies and facilitating partnerships.
- Ensuring that results and assessments of monitoring and research efforts are accessible to and understandable by managers, policy makers, and the general public.
- Ensuring that ocean acidification data are properly managed and integrated across disciplinary, organizational, and data management technology boundaries.

As ocean acidification monitoring, research, modeling, and outreach programs are developed, priorities will likely need to be adjusted to ensure coverage of all present and future needs. Areas that are especially vulnerable to ocean acidification in the near-term, particularly high-latitude open-oceans, coral reefs, and coastal regions including estuaries, will receive special emphasis throughout the program and are incorporated into the short-term and/or long-term goals of each theme.

The establishment of a National Ocean Acidification Program, and an associated National Program Office, is recommended to serve the vital role of developing and executing an implementation plan that aligns with the goals in this strategic research plan. The location and leadership model for the National Ocean Acidification Program Office should be determined by the participating agencies once the National Ocean Acidification Program is confirmed. The National Ocean Acidification Program Office will report directly to the IWG-OA and be tasked with developing an ocean acidification implementation plan, coordinating Federal and federally-funded ocean acidification research and monitoring, establishing an ocean acidification information exchange, and producing reports and documentation as required by the FOARAM Act and other statutes and interagency mandates. Both the IWG-OA and National Ocean Acidification Program must ensure that Federal ocean acidification monitoring, research, funding programs, and outreach efforts effectively address short- and long-term priorities, while remaining proactive and adaptive as ocean acidification impacts and effective mitigation measures become better understood.

Legislative Mandate

The Federal Ocean Acidification Research and Monitoring Act of 2009 (FOARAM Act) directed the Subcommittee on Ocean Science and Technology (SOST) to create an Interagency Working Group on Ocean Acidification (IWG-OA). The IWG-OA was chartered by SOST in October 2009 and includes representatives from the National Oceanic and Atmospheric Administration (NOAA), National Science Foundation (NSF), Bureau of Ocean Energy Management (BOEM), U.S. Department of State (DOS), U.S. Environmental Protection Agency (EPA), National Aeronautics and Space Administration (NASA), U.S. Fish and Wildlife Service (FWS), U.S. Geological Survey (USGS), and the U.S. Navy. NOAA chairs the group, and the vice-chair is from NSF. The agencies represented in the IWG-OA have mandates for research and/or management of resources likely to be impacted by ocean acidification (Appendix 1). The group meets regularly to coordinate ocean acidification activities across the Federal government to fulfill the goals of the FOARAM Act.

Section 12404(c) of the FOARAM Act further specifies that the SOST will, not later than 2 years after the date of enactment of the FOARAM Act, transmit a strategic research plan, outlined under section 12405 of the FOARAM Act, to the Committee on Commerce, Science, and Transportation of the Senate and the Committee on Science and Technology and the Committee on Natural Resources of the House of Representatives. Section 12405 of the FOARAM Act states that the strategic plan "will provide for an assessment of the impacts of ocean acidification on marine organisms and marine ecosystems and the development of adaptation and mitigation strategies to conserve marine organisms and marine ecosystems." In addition, the FOARAM Act sets forth the contents, program elements, review, and public participation for the strategic plan.

National Ocean Policy

On July 19, 2010, the President signed an Executive Order establishing the nation's first comprehensive National Policy for the Stewardship of the Ocean, Our Coasts, and Great Lakes and adopted the Final Recommendations of the Ocean Policy Task Force (OPTF 2010). The Final Recommendations identify global climate change, ocean acidification, and their associated impacts on oceans, coastal regions, and the Great Lakes as some of the most serious threats to these ecosystems and coastal communities. Highlighting the importance of these issues to the United States, one of the nine National Priority Objectives listed by the OPTF is: "Resiliency and Adaptation to Climate Change and Ocean Acidification." The development of a strategic research plan for ocean acidification, as requested by the FOARAM Act, is a necessary early step towards achieving this National Priority Objective.

Strategic Plan for Federal Research and Monitoring on Ocean Acidification

Introduction and Background

Human industrial and agricultural activities have caused global atmospheric concentrations of carbon dioxide (CO_2) to increase from a pre-industrial average of 280 parts per million (ppm) to the current value of approximately 390 ppm. Atmospheric CO_2 concentrations are now higher than experienced on Earth for more than 800,000 years (Lüthi *et al.* 2008), and the rate of CO_2 release into the atmosphere is likely unprecedented in Earth history (Kump *et al.* 2009).

Ocean carbonate chemistry is a natural buffering system, but this buffering capacity is being compromised as a direct result of CO_2 absorption by the oceans. The oceans have absorbed approximately half of the anthropogenic CO_2 emissions from fossil fuel use and cement manufacturing over the past 200 years (Sabine *et al.* 2004). This oceanic uptake of CO_2 causes changes to ocean chemistry (Figure 1), including decreases in pH and carbonate ion (CO_3^{2-}) concentrations, collectively known as global ocean acidification (Figure 2). Since the beginning of the industrial revolution, this uptake has caused a lowering of the surface ocean pH from about 8.2 to 8.1 (Caldeira and Wickett 2003, Feely *et al.* 2004, Caldeira and Wickett 2005), which corresponds to a 30% increase in acidity (concentration of hydrogen ions, H^+). Reconstruction of past sea surface conditions suggest surface ocean pH has not been this low for at least 2 million years (Hönisch *et al.* 2009), and Orr *et al.* (2005) predicted an additional decrease in average global surface ocean pH of 0.3 to 0.4 over the 21st century. As a consequence of ocean acidification, the chemistry of the oceans is presently changing at a rate exceeding any known to have occurred for at least the past 20 million years (Feely *et al.* 2004).

It is not presently known how the changes in seawater chemistry due to ocean will affect marine organisms and ecosystems, though potential responses of some organisms have been examined and changes in marine ecosystems appear likely based on current information (Raven *et al.* 2005). Some organisms appear to be particularly sensitive, while others are not (Doney *et al.* 2009, Ries *et al.* 2009). Ocean acidification can negatively impact organisms that use calcium carbonate ($CaCO_3$) to build their shells or skeletons (e.g., corals, marine plankton, and shellfish) because it reduces the availability of carbonate ions, which play an important role in shell formation (calcification). Changes in CO_2 and pH can impact other physiological processes as well, affecting species growth, survival, and behavior (Pörtner 2008). There will likely be ecological winners and losers as a result of ocean acidification, causing shifts in the structure and composition of marine food webs and ecosystems.

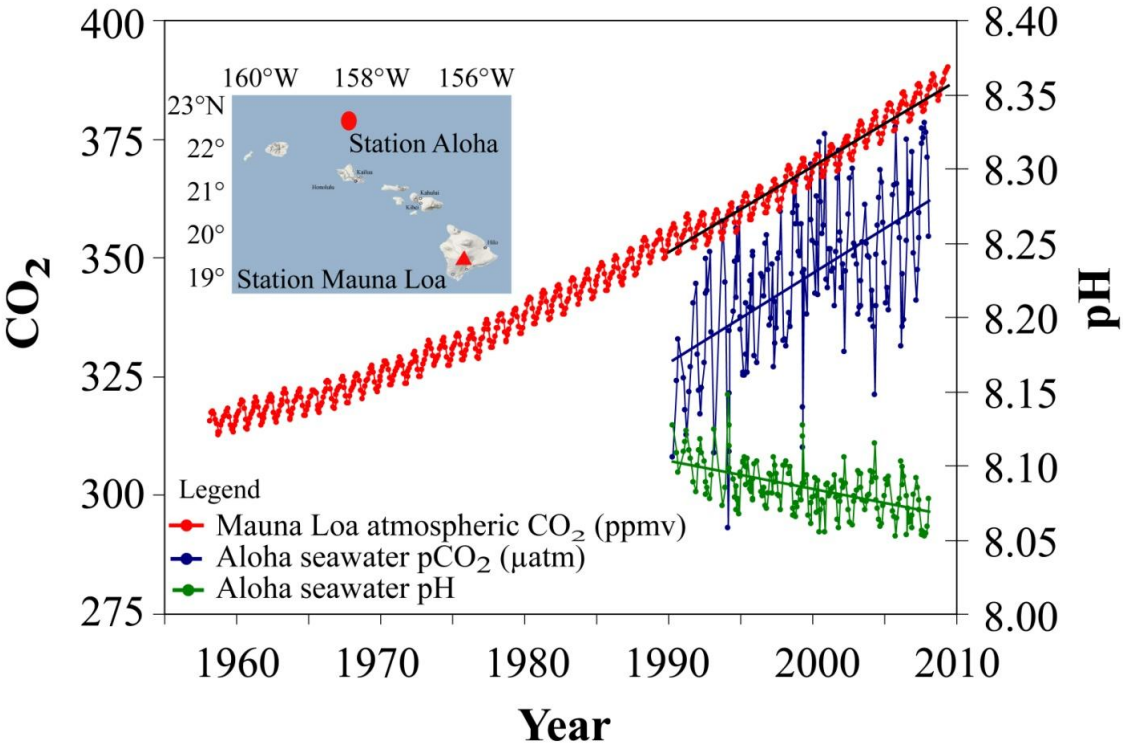


Figure 1. Time-series of atmospheric CO_2 at Mauna Loa, Hawaii (in parts per million volume, ppmv; in red), surface ocean pCO_2 (µatm; in blue) and surface ocean pH (in green) at Ocean Station ALOHA in the subtropical North Pacific Ocean. Note that the increase in oceanic CO_2 over the past 17 years is nearly consistent with the atmospheric increase within the statistical limits of the measurements. Modified after Doney *et al.* 2009 (Mauna Loa data courtesy of Dr. Pieter Tans, NOAA/Earth System Research Laboratory; Hawaii Ocean Time-Series/ALOHA data courtesy of Dr. David Karl, University of Hawaii; see also Dore *et al.* 2009).

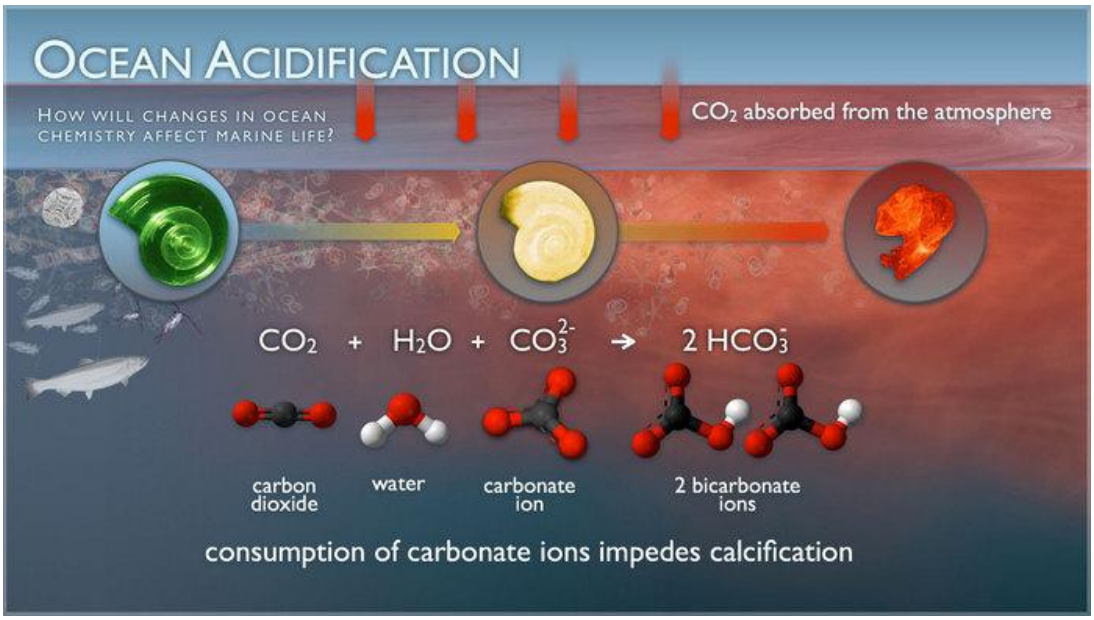


Figure 2. Schematic diagram of ocean acidification processes in the sea (image provided by the NOAA Pacific Marine Environmental Laboratory Carbon Group in collaboration with the University of Washington Center for Environmental Visualization).

Strategic Research Plan

A strategic plan is essential to guide Federal ocean acidification investments and activities over the next decade. Although many Federal agencies currently conduct ocean acidification research and monitoring (Appendix 1), these activities are largely uncoordinated and are not driven by a common vision or purpose. The risk is that agency efforts will be duplicative, or worse, that critical research will not be conducted.

This strategic plan presents a clear vision and specific goals to move Federal agencies toward a better understanding of the process of ocean acidification, its effects on marine ecosystems, and the steps that must be taken to adapt management to account for it. Under this plan, the next decade will bring about the implementation of a comprehensive global and regional ocean acidification observing system that includes the monitoring of biological effects. Researchers will quantify the physiological effects of ocean acidification, under a range of scenarios, on a wide variety of marine organisms. Enhanced modeling efforts will lead to improved understanding of the global biogeochemical processes of ocean acidification and its impact on marine ecosystems. A National Ocean Acidification Program will be established to lead U.S. coordination of ocean acidification activities between the Federal agencies, and with academic institutions, industry, and other private sector and international partners. A national ocean acidification data management and information exchange program will ensure that ocean acidification information reaches scientists, decision makers, and the public in a timely manner. For example, the data and information generated through this plan could potentially be used by States to help them better address ocean acidification impacts in their coastal waters under various Clean Water Act programs. Finally, the U.S. will join other countries in establishing a robust international research program to address what is truly a global challenge.

In order to address the complexity of the expected changes, this strategic research plan is organized into seven priority themes to guide Federal activities in addressing ocean acidification. The themes include the five Program Elements set forth as the minimum requirement in the FOARAM Act and two elements inherent to successful implementation of the plan:

- Theme 1, “Monitoring of Ocean Chemistry and Biological Impacts,” identifies sampling programs that collect ocean acidification data, and it prioritizes additional monitoring systems necessary for adequate data collection and monitoring.
- Theme 2, “Research to Understand Responses to Ocean Acidification,” describes the goals and priorities to understand the physiological responses of marine organisms to ocean acidification and its interactions with other stressors, the impacts to marine food webs, and possible approaches to track ecosystem responses.
- Theme 3, “Modeling to Predict Changes in the Ocean Carbon Cycle and Impacts on Marine Ecosystems and Organisms,” summarizes requirements and recommendations for modeling ocean acidification, and its impacts on marine organisms and ecosystems, including codifying our research understanding and studying the interplay of factors affecting marine ecosystems, thus permitting analysis of the efficacy of adaptation and mitigation strategies.
- Theme 4, “Technology Development and Standardization of Measurements,” describes goals that ensure the ability to measure all required parameters through technology development and adequate data quality via measurement standardization.

- Theme 5, "Assessment of Socioeconomic Impacts and Development of Strategies to Conserve Marine Organisms and Ecosystems," focuses on assessing the socioeconomic impacts of ocean acidification and developing adaptation and mitigation strategies.
- Theme 6, "Education, Outreach, and Engagement Strategy on Ocean Acidification," describes goals for designing and coordinating educational, public outreach, and domestic and international engagement activities, as well as ensuring results and assessments of monitoring and research efforts are accessible to and understandable by all stakeholders.
- Theme 7, "Data Management and Integration," discusses the need for effective data management and integration within the context of other international, Federal, State, local and private activities.

This strategic plan builds upon numerous reports and studies that have been supported over the recent past by U.S. Federal agencies and other entities. Some of the major reports considered are:

- 2010 National Research Council (NRC) report, *Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean* (NRC 2010a). This report is a review of the state of knowledge and identifies key gaps in information to help Federal agencies develop a National Ocean Acidification Program to improve understanding and address the consequences of ocean acidification.
- Community White Papers for OceanObs'09: Sustained Ocean Observations and Information for Society (Hall *et al.* 2010 and papers therein). White papers describe observing systems, sensors, and data management critical to an ocean acidification program.
- 2008 Report of the Ocean Carbon and Biogeochemistry Scoping Workshop on Ocean Acidification Research, *Present and Future Impacts of Ocean Acidification on Marine Ecosystems and Biogeochemical Cycles* (Fabry *et al.* 2008). This report outlines research activities needed to advance ocean acidification research across four critical ecosystems: high-latitude regions, warm and cold water coral reefs, coastal regions including estuaries, and tropical/subtropical pelagic regions.
- *Report on Research Priorities for Ocean Acidification* (Orr *et al.* 2009). This report resulted from the Second Symposium on the Ocean in a High-CO_2 World held in 2008, which provided an interdisciplinary forum to assess what is known about ocean acidification and priorities for future research.
- *Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A Guide for Future Research* (Kleypas *et al.* 2006). This workshop report identifies the most pressing questions about the effects of rising atmospheric carbon dioxide on marine calcifiers, ecosystems, and the carbon cycle. It also provides guidelines for designing research to address these questions.
- 2005 Royal Society Report, *Ocean Acidification Due to Increasing Atmospheric Carbon Dioxide* (Raven *et al.* 2005). This report provides an overview of the state of scientific knowledge of ocean acidification and its likely impacts on marine organisms.

Establishment of a National Ocean Acidification Program

It is recommended that a National Ocean Acidification Program, and associated National Program Office, be established to ensure coordination and integration of Federal ocean acidification research and monitoring activities, with oversight by the IWG-OA. The location and leadership model for the National Ocean Acidification Program Office should be determined

by the participating agencies once the National Ocean Acidification Program is established, and the Office should leverage existing Federal programs so that there are no additional administrative costs. The National Program Office should be supported cooperatively by participating agencies.

The National Ocean Acidification Program should:

- Develop a detailed implementation plan with community input.
- Establish, and support the activities of, a committee that helps identify the needs for research, monitoring, education, outreach, and other appropriate activities.
- Coordinate and assist with planning of Federal and federally-funded ocean acidification research and monitoring activities.
- Act as a Federal nexus for State, local, and private-sector partners.
- Coordinate U.S. ocean acidification research and monitoring with international activities.
- Establish an ocean acidification information exchange to provide timely research results and produce syntheses and assessments that will be accessible to and understandable by managers, policy makers, and the general public. The information exchange will serve as a communication avenue between the National Program, scientists, managers, and others seeking decision support.
- Support workshops, advisory group meetings, etc. to develop plans, integrate activities and communicate issues, activities, and results.
- Develop a comprehensive data management plan.
- Provide input for reports to Congress and other documentation as required by the FOARAM Act and other statutes and interagency mandates.

Theme 1. Monitoring of Ocean Chemistry and Biological Impacts

Monitoring of the oceans on appropriate spatial and temporal scales is critical to understanding ocean acidification and associated environmental changes. Carbonate chemistry observations have begun to address ocean acidification in open-ocean locations through the global oceanic carbon observatory network of repeat hydrographic surveys, time-series stations (ship-based and moored), and ship-based underway surface observations in the Atlantic, Pacific, and Indian Oceans. Carbon observing networks do not, however, exist for coastal and estuarine environments. Enhancing open-ocean carbon monitoring activities and expanding these networks into coastal and estuarine regions is essential to understanding and predicting responses of marine biota to ocean acidification, as well as changes in ecosystem processes, biogeochemistry, and climate feedbacks.

Requirements and Recommendations

Determining the changes in seawater chemistry and biology in a rising CO_2 world is vital for understanding the ecosystems changes that will ultimately control the size and composition of our fisheries and other biological resources. Ocean acidification monitoring and research focuses on four carbon parameters: partial pressure of carbon dioxide (pCO_2), pH, total alkalinity (TA), and dissolved inorganic carbon (DIC). Monitoring efforts should measure a minimum of two of these parameters to allow determination of all carbon species and parameters and to ensure internal consistency of the data. These parameters, as well as temperature, salinity, oxygen, nutrients, dissolved organic carbon (DOC), and particulate organic- and inorganic carbon (POC, PIC), can be measured routinely onboard ships. Data for these same parameters should be collected from open-ocean, coastal, and estuary waters. While some portion of these chemical species now can be measured on moorings and floats in open water systems, they are not yet broadly utilized on a global scale including coastal and estuarine systems. The chemical measurements described above are critical for validation of sensors, development of proxy methods, and assessment of accuracies.

Primary production, carbon and nitrogen fixation, metabolism, and biological species composition are important biological measurements to correlate with chemical indicators of ocean acidification. Correlations may provide insight to population- and community-level effects and could ultimately lead to development of biological indicators. The National Ocean Acidification Program will need to incorporate a process for identifying issues to be addressed by biological indicators (Theme 2) and guidelines for developing the indicators and vetting their performance (e.g., Jackson *et al.* 2000; Theme 4). Of particular importance is development of indicators that characterize biological effects with major long-term ecological or economic consequences, are responsive to ocean acidification over other environmental variables, have the power to detect meaningful differences, and can be applied at fairly broad spatial scales with relatively low cost. As biological indicators are developed and integrated with process studies (Theme 2), they will need to be adapted into long-term field monitoring plans (NRC 2010a).

Strategy for Coordinating an Observational Network for Ocean Acidification

Many of the same sampling principles and strategies that are being developed for open-ocean and coastal carbon and biogeochemical repeat hydrographic surveys and time-series stations

apply to the development of an observational network for ocean acidification. Consequently, most of the planning towards integrating hydrographic surveys and time-series measurements should be focused into a single coordinated effort using the interagency resources and infrastructures that presently exist for high-latitude regions, warm and cold water coral reefs, coastal regions including estuaries, and tropical/subtropical pelagic regions. Monitoring in these regions reflects the need to better understand global variations in ocean sensitivity to acidification. Regions with strong upwelling regimes (such as the U.S. West Coast) could be more vulnerable, because upwelled waters are naturally higher in CO_2 (and thus lower in pH); coastal regions with high freshwater input from rivers may also be more vulnerable to acidification because fresh water has a decreased ability to neutralize acids, in general, and may carry other acidifying solutes. Ocean acidification may be exacerbated in polar ecosystems, as CO_2 is more soluble in colder water, and the loss of sea ice in summer results in greater exposure of seawater to the atmosphere, allowing more exchange of CO_2 across the ocean-atmosphere interface. Fresh water dilution, from arctic ice melt, at high latitudes also exacerbates acidification and results in under-saturation of carbonate minerals. However, it should be noted that low latitude systems are not immune to such changes. In fact the greatest rate of change in carbonate mineral saturation state has been observed within the Atlantic tropical waters where coral growth rates and declines in proportion to changing carbonate mineral saturation state are already being observed. Additionally, the U.S. efforts should coordinate and collaborate with international activities as appropriate (Theme 6).

Additional chemical and biological measurements, such as highly resolved depth distributions and abundances of calcifying plankton, estimates of $CaCO_3$ calcification and dissolution rates, and other CO_2-sensitive processes as appropriate, should be added to existing repeat surveys to monitor ocean acidification and its associated impacts. Likewise, opportunities for development of new long-term monitoring systems should be explored to fill any data collection gaps identified in priority areas such as high-latitude regions, warm and cold water coral reefs, and coastal regions and estuaries.

The sampling plans for the next phase of the World Climate Research Programme's (WCRP) Climate Variability and Predictability (CLIVAR)/CO_2 Repeat Hydrography Program (also referred to as GO-SHIP [Global Ocean Ship-based Hydrographic Investigations Program]) can effectively provide the required long timescale information for the ocean acidification network (Figure 3). Spatial sampling should continue to repeat the transect lines carried out in the Atlantic, Pacific, and Indian Oceans, with the Southern Ocean integrated as part of the other basins. The Arctic is of increasing importance and should be emphasized (Robbins *et al.* 2010) by establishing a monitoring effort in appropriate locales.

For shallow water coastal and estuarine environments and areas inaccessible by open-ocean ships, a similar sampling strategy as outlined for the open-ocean carbon measurements is recommended, but at much higher temporal and spatial resolution than for the open ocean. These activities will be integrated with ongoing ship-based surveys in coastal areas, but at higher frequencies as required.

Underway sampling on research vessels and Voluntary Observing Ships (VOS) from the U.S. and other countries should be taken advantage of by including the additional pH, carbon, and

biological parameters necessary to address ocean acidification and acidification impacts (Figure 4). These data would help establish large-scale trends in ocean acidification in much the same way as established basin-scale trends in pCO_2. Additional biological parameters, including those identified by ongoing and future research (Theme 2), should be included to assess ecosystem responses to ocean acidification (see above).

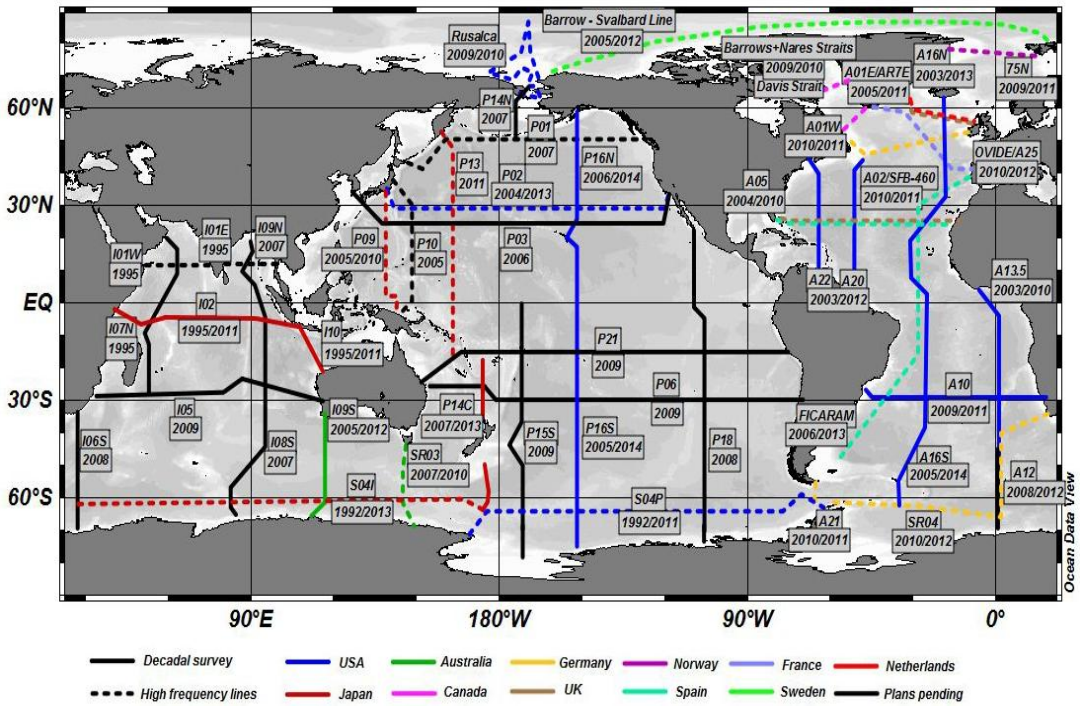


Figure 3. Planned CLIVAR/CO_2 Repeat Hydrography surveys and high-frequency lines for carbon and ocean acidification measurements (after Feely *et al.* 2010).

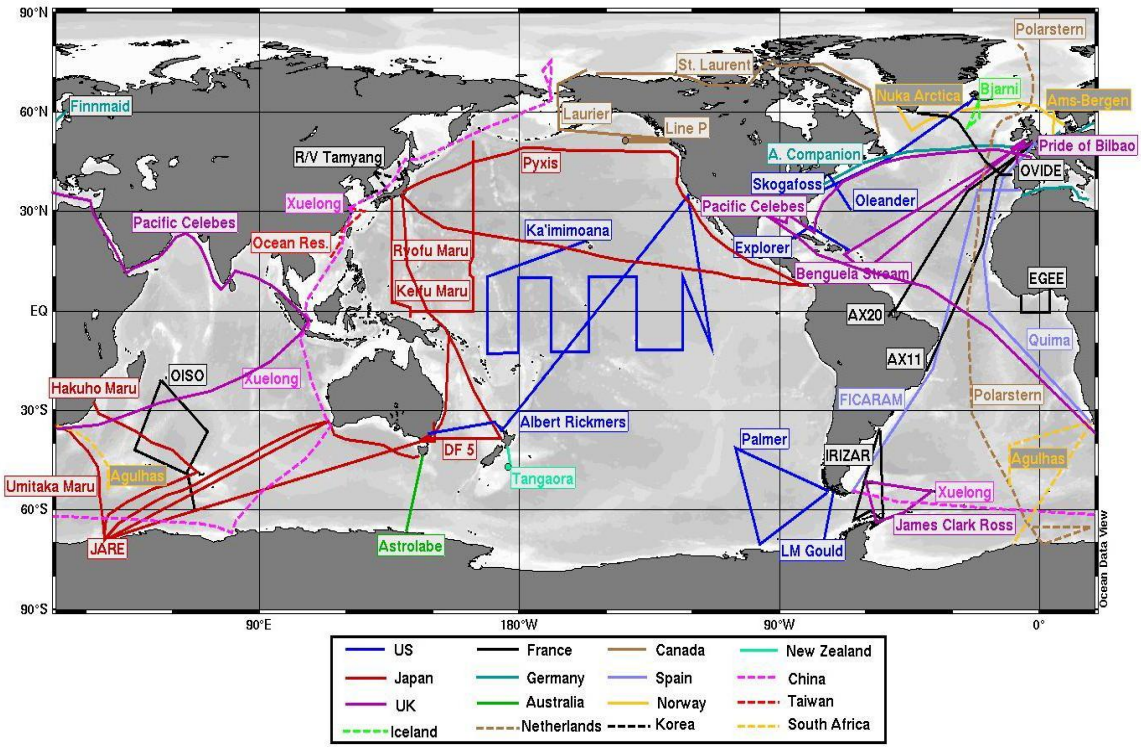


Figure 4. Planned underway VOS surveys for surface ocean measurements of pCO_2 and other carbon and biological parameters (after Feely *et al.* 2010).

Time-series Measurements at Fixed Stations

Time-series stations are urgently needed in the open-ocean, coastal regions, and estuaries to document high frequency variations in ocean acidification relevant parameters (Figure 5; e.g., Dore *et al.* 2009). Existing observing systems that are already conducting time-series measurements should be given priority for inclusion in the ocean acidification monitoring program (refer to Box 1 for examples). By enhancing a subset of these time-series locations with the appropriate chemical and biological sensors, an ocean acidification network can be developed at reasonable costs. For example, some buoys in existing programs should be equipped with carbon system sensors for ocean acidification. Additionally, bio-optical sensors and optical plankton imaging systems should be deployed to track possible shifts in abundances of key biological functional groups (e.g., calcifying phytoplankton and small mollusks called pteropods). Seasonal measurements of calcification rates and other CO_2-sensitive processes not currently measured at time-series sites are necessary to assess the long-term response of ecosystems to ocean acidification.

In addition to expanding ocean acidification monitoring into existing monitoring networks; efforts should be placed on the compilation of the existing historic datasets. The Ocean Carbon Board (OCB; http://www.us-ocb.org/publications/EPA_OCB_FINAL.pdf) recommended that the EPA "seek out long-term coastal States' and Federal datasets (e.g., USGS, NOAA) on water quality or any monitoring studies that have included pH data collected in coastal State waters." These data may provide information on the natural variability within estuarine and coastal systems and the dominant factors influencing pH in different types of estuaries.

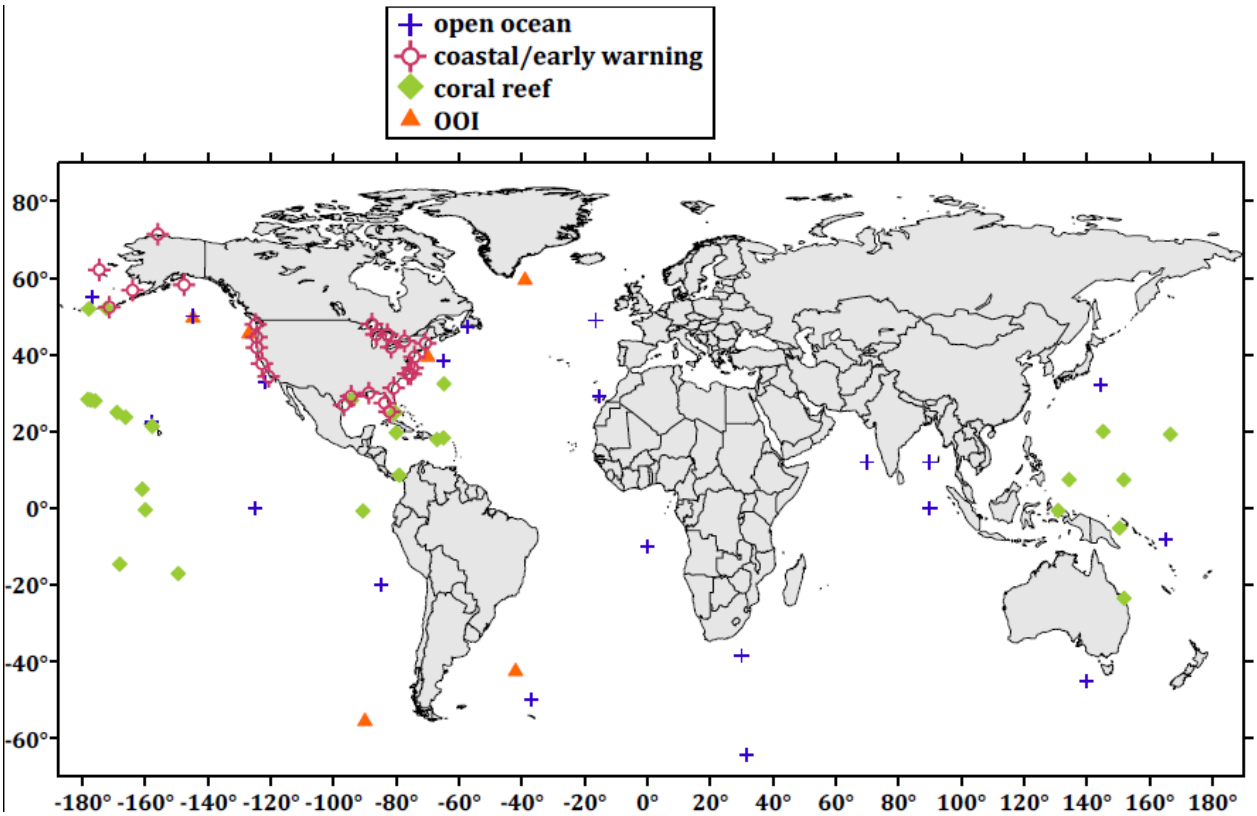


Figure 5. Planned U.S. carbon and acidification monitoring sites in open-ocean, coastal ocean, and coral reef regions for time-series measurements and process studies. (from NOAA Ocean and Great Lakes Acidification Research Plan, April 2010; refer to Feely *et al.* 2010 for information on internationally coordinated moorings).

Box 1. Examples of existing, major observing programs that collect time-series measurements at fixed stations and could be augmented with ocean acidification measurements.

- *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 (OOI)* is constructing a networked infrastructure of science-driven sensor systems to measure physical, chemical, geological, and biological variables in the ocean and seafloor. The network will include coastal and open-ocean assets adjacent to the U.S., as well as global assets elsewhere in the world's ocean, particularly the high latitudes.

- The *Integrated Ocean Observing System (IOOS)* is a Federal, regional, and private sector partnership that collects and delivers valuable oceanographic data along our coasts.

- The *National Association of Marine Laboratories (NAML)* is a nonprofit organization representing marine and Great Lakes laboratories. Member institutions have long-term data sets for various physical and biological parameters, as measured from docks, water intake systems, or frequently monitored shallow-water sites.

- The EPA *National Estuary Program (NEP)* is a Federal program established to improve the quality of 28 estuaries of national importance distributed across the U.S. coastline. The EPA works with States to maintain high water quality in these estuaries and can incorporate new instrumentation and methods for monitoring acidification and its effects in estuaries.

- The NOAA/National Ocean Service (NOS) *National Estuarine Research Reserve System (NERRS)* 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 (NOS) *National Marine Sanctuary Program (NMSP)* 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 (SWiM).

- The *Long-Term Ecological Research (LTER) 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.

- The *NOAA Coral Reef Conservation Program (CRCP)* maintains a set of time-series stations and satellite observations to provide coral reef managers, scientists, and other users worldwide with information and forecasts of coral bleaching events using sea surface temperature data.

- The *National Park Service Inventory and Monitoring (I&M) Program* provides a set of 12 baseline natural resource inventories on National Parks, which include coastal and estuarine locations. Natural resource inventories are extensive point-in-time surveys to determine the location or condition of a resource, including the presence, class, distribution, and status of biological resources such as plants and animals, and abiotic resources such as air, water, soils, and climate in certain coastal and estuarine locations. The NPS *I&M Vital Signs Monitoring Program* measures physical and biological indicators of ecosystem condition across networks of parks in bioregions.

Box 1. Continued.

- The *National Wildlife Refuge System Inventory and Monitoring Program* is a component of the National Biological Inventory and Monitoring Partnership for the FWS National Wildlife Refuge System (NWRS). It includes a suite of monitoring parameters to assess impacts of increasing seawater pH on coral organisms and other reef building species. Research will include assessing the indirect effects of ocean acidification on islands on atolls related to ocean acidification and other climate change phenomena. The NWRS can serve as a natural laboratory for monitoring and research on the effects ocean acidification, including sites in the remote Pacific Ocean.

Time-series Measurements on Floats and Gliders

Carbon and pH sensors on autonomous floats and gliders could resolve shorter space-time scale variability of the upper ocean more readily than repeat sections, but the sensor technology must be developed and tested in the field before it can be implemented on a large scale (Theme 4). In the meantime, the addition of oxygen sensors would rapidly and inexpensively enhance the biogeochemical relevance of existing floats (such as those in the Argo Program: www.argo.ucsd.edu), and the data could be utilized to directly address ocean acidification issues via appropriate algorithm development (Juranek *et al.* 2009). Further development of these sensor packages and algorithms for ocean acidification will be emphasized and coordinated with satellite remote sensing activities (below).

Remote Sensing

Satellites can provide synoptic observations of a range of physical and optical parameters that allow us to model changes in the distribution of carbonate chemistry within the surface ocean where no *in situ* observations are available. Through the application of a variety of techniques, satellite observations are being applied to extend *in situ* carbonate chemistry measurements over broader scales, permitting examination on spatial and temporal scales not practical through *in situ* observations alone (e.g., Gledhill *et al.* 2008). The success of local algorithms to predict episodic events (Juranek *et al.* 2009) could potentially be extended using satellite remote sensing. Remote sensing has also had success (Balch *et al.* 2007) observing important classes of phytoplankton (i.e., calcifying species known as coccolithophorids) that strongly interact with the carbonate cycle and will be directly affected by ocean acidification.

Goals

The National Ocean Acidification Program monitoring plan should be designed to rapidly characterize the magnitude and extent of acidification through a comprehensive monitoring effort at global, regional, and local scales. This information is required to develop robust ecological and socioeconomic projections of future impacts of ocean acidification in order for policy makers, managers, and local stakeholders to make informed decisions (NRC 2010a, Ocean Research and Resources Advisory Panel [ORRAP] 2010). The monitoring plan should be designed to maximize collaborations and thus leverage planned and existing observing assets, nationally and internationally. Most of the monitoring goals listed below are receiving some attention already. The short-term goals address issues that could be resolved quickly with

adequate funding. The long-term goals should also be addressed as soon as possible, but they may take longer to yield their full benefits and/or require completion of one or more short-term goals.

Short-term (3-5 years)

- Evaluate the geographical extent and capabilities of existing monitoring systems in regions and habitats where ocean acidification effects are most likely and subsequently identify:
    - Systems which should be utilized and expanded; and
    - Regions and habitats where new systems may be warranted.
- Expand existing coastal and ocean measurements by deploying new ocean acidification monitoring instrumentation on research ships, volunteer observing ships, moorings, floats, and gliders.
- Identify and deploy monitoring instrumentation in coastal and estuarine sites to extend the open-ocean monitoring parameters and methods to these shallow water systems.
- Document trends in ocean acidification and biological responses that can be used for real-time early warning systems and for verification of computer model outputs.
- Improve adoption of standardized chemical and biological monitoring protocols.
- Develop new technology that will allow for accurate *in situ* measurements of the carbon system and biological responses (Theme 4).
- Develop biological monitoring protocols.

Long-term (10 years)

- Expand and complete ocean acidification global monitoring network;
- Expand and complete ocean acidification network for coastal regions and estuaries;
- Continue development of biological monitoring protocols; and
- Integrate new protocols into global monitoring system.

Budget

The President's FY 2012 Budget proposed $9.65 million to support the monitoring efforts for the National Ocean Acidification Program, as described above in Theme 1 (see Appendix 2 for more details). Agencies presently supporting ocean acidification monitoring efforts include NASA, NOAA, NSF, and USGS. New chemical and biological ocean acidification sensors would be deployed on research cruises, moorings, gliders, and floats. The overall number of deployed sensors would be increased over time and maintained for the duration of the program.

Theme 2. Research to Understand Responses to Ocean Acidification

The effects of ocean acidification and other variables affected by climate change on marine ecosystems need to be understood and the potential for adaptation assessed to correctly predict future changes caused by ocean acidification.

Numerous studies have tested the potential effects of ocean acidification on marine organisms (Gattuso *et al.* 1998, Kleypas *et al.* 1999, Hoegh-Guldberg *et al.* 2007, Iglesias-Rodriguez *et al.* 2008, Pelejero *et al.* 2010). Ocean acidification may threaten whole marine ecosystems and the services they provide. More research is needed to better inform models and improve predictions of the impacts of ocean acidification on marine populations and communities and the capacity of organisms to acclimate or adapt to the changes occurring in ocean chemistry.

The most significant research challenges are to separate the effects of ocean acidification from other environmental stressors and to estimate the synergistic effects of ocean acidification with other stressors to correctly predict future conditions threatening ecosystems and human populations. Little is known about how changing ocean chemistry will affect global ocean biogeochemical cycles of biologically important elements and nutrients. A fundamental understanding of the impact of ocean acidification on marine organisms, communities, and ecosystems is needed to develop effective mitigation strategies to increase resilience of ecology and economically important organisms and ecosystems.

Current understanding of ocean acidification impacts on ecosystem has been documented in comprehensive reviews (e.g., Raven *et al.* 2005, Kleypas *et al.* 2006, Fabry *et al.* 2008, Doney *et al.* 2009, NRC 2010a). The research needs, recommendations, and goals below focus on major priorities for federally supported research on ocean acidification, and they are based mainly on the NRC (2010a), Orr *et al.* (2009), Fabry *et al.* (2008), and Royal Society (Raven *et al.* 2005) reports.

Requirements and Recommendations

A successful strategy for ocean acidification research requires special attention to integrated efforts, regionally, nationally, and internationally. Effective management of marine resources in response to ocean acidification will require researchers' viewing their contributions in a broader perspective, but there is also clearly a need for research on issues such as vulnerable and economically important species to be conducted at regional scales. To this end, conducting studies on an expanding list of species, rather than focusing resources on in depth studies of a narrow group of species, should be encouraged. Large facilities and highly interdisciplinary training opportunities will be needed to help scientists succeed in this new field, scale up experiments to the ecosystem-level, and develop useful marine ecosystem management strategies. Additional investments in technology development will be useful to improve the capability to measure chemical and biological variables over space and time (NRC 2010a).

A solid understanding of the impacts of ocean acidification on marine organisms and ecosystems is critical to developing early warning systems (Theme 1), predictive models (Theme 3), and indices that will guide adaption and mitigation measures (Theme 5). Critical research efforts

include: understanding species-specific physiological responses; understanding how effects on organisms will propagate through food webs and ecosystems; developing indices that capture shifts in environmental and ecological responses; and understanding earth history to inform ocean acidification predictions.

Species-specific Physiological Responses

Biological response of marine organisms to ocean acidification impacts seems to be species-specific, with potential "winners" and "losers" emerging (NRC 2010a). Research has shown calcification rates will decrease for most species (Guinotte and Fabry 2008), and that calcification is not the only biological process that is critically influenced by a changing pH and increased CO_2 concentration (Pörtner 2008). While it is important to be able to quantify changes in calcification rates simultaneously with other physiological processes, few studies have successfully done this. The biochemical reactions of organisms are profoundly impacted by pH, and unless species can acclimate, avoid, or adapt metabolically, survival may be compromised.

Understanding the magnitude of these biological changes on ecologically important organisms is essential to predicting possible impacts of ocean acidification on the structure of marine communities. Similarly, focusing on economically important species is key to predicting possible impacts on the industries and human communities depending upon them. Priority should be given to studies taking a "whole-organism" approach that quantifies changes in calcification rates simultaneously with other physiological factors (e.g., changes in metabolism, health, and behavioral responses) to maximize the probability of detecting ecologically and economically important effects and those that may offset effects of ocean acidification (Findlay *et al.* 2009). After clear positive or negative organism responses to changes in pH or saturation states are identified, species-specific mechanisms that cause those responses should be determined.

Changes to seawater chemistry have been occurring very rapidly on geochemical and evolutionary timescales and there is a justifiable concern as to whether organisms will be able to acclimate or adapt to these changes (NRC 2010a). Research on species acclimation (individual organism adjustment) and adaptation (population change with time) is necessary to correctly predict future biological response to ocean acidification and the ecosystem impacts. For some organisms, longer term, multi-year studies using realistic CO_2 levels (e.g., those projected for next 100 years) should be emphasized rather than acute effect (very high CO_2 levels) short-term studies (Pörtner 2008); however, short-term acute exposure experiments with increases in magnitude of variability (e.g., pH) may be appropriate for those organisms that experience strong diel-cycling of pH and in coastal systems experiencing increased frequency or severity of upwelling or other acute conditions. Various tools have been developed to evaluate evolutionary mechanisms under ocean acidification and to study the potential for species-specific acclimation. These include:

- Controlled laboratory studies;
- Biogeochemical proxy development and paleo-reconstructions;
- Studies located at seafloor vents where high concentrations of CO_2 are emitted to the water column at ambient temperature;
- Studies in regions with naturally high variability in carbon chemistry, such as coastal and upwelling systems; and

- Genomic and proteomic studies designed to investigate physiological plasticity and adaptive capacity in response to ocean acidification.

Studies investigating the effects of CO_2 on physiological processes should also be conducted in conjunction with those that examine other factors such as temperature and oxygen deficiency because ocean acidification will not be affecting any system in an isolated way. Little is known about the simultaneous effects of ocean acidification and warming on physiological processes (Kleypas and Langdon 2006); however, a few studies suggest that annual average coral reef calcification rate may actually increase as ocean warms (McNeil *et al.* 2004). Biological response and changes in marine ecosystems cannot be realistically understood without at least accounting for the effects of climate change simultaneously with elevated seawater pCO2 and decreased pH. These phenomena are intrinsically coupled as they have the same primary cause: anthropogenic emission of CO_2.

A diverse set of organism types (i.e., different taxa, trophic levels, etc.) must receive attention to achieve robust understanding and predictive capabilities with respect to ecosystem responses, especially those predicted to be most negatively impacted by ocean acidification and those most relied upon for ecosystem services. Understudied groups of organisms (Raven *et al.* 2005, Kleypas *et al.* 2006, Joint *et al.* 2010) which require attention include:

- Deep, cold-water, stony corals, especially major reef builders;
- Calcifying and non-calcifying primary producers such as crustose coralline algae, phytoplankton species, sea grasses, and kelp, as well as harmful algal species;
- Calcifying bivalve and crustacean species which have commercial, ecological, and/or cultural importance;
- Key calcifying zooplankton species which provide the critical link between primary production and major commercial fishery species;
- Species with large economic importance such as various fish and squid species; and
- Other non-calcifying, ecologically key (and sometimes invasive) species such as tunicates, jellies, and microbes which contribute strongly to ecosystem function and process.

Food Webs and Ecosystems

The effects of ocean acidification on specific organisms will propagate through food webs, altering community dynamics, such as predator-prey and competitive interactions. Research is needed to determine how and where this will happen. Ecosystem models (linked to biogechemical and hydrodynamic models) will be an important tool for forecasting the impact of ocean acidification on ecological communities (Theme 3).

Species and ecosystems may acclimate or adapt to ocean acidification and associated changes in primary productivity and nutrient availability. Furthermore, higher trophic levels may be affected by changes to quantity or composition of the food available and by direct physiological effects (NRC 2010a). Research that explores how rising ocean temperatures, elevated CO_2, and decreased pH act simultaneously on the distribution of primary producers and then on the higher trophic levels of marine food webs is in its infancy. If decreased biodiversity results from ocean acidification, the stability of ecosystems may be compromised by the possible loss of key trophic linkages and food web integrity and/or an inhibition of ecosystem resilience. Such changes could result in alternative ecosystem states, and ultimately, lead to catastrophic ecosystem changes

(NRC 2010a). Vulnerable ecosystems include cold- and warm-water coral reefs (Figure 6); coastal ecosystems subjected to upwelling conditions, especially in the high latitudes; and estuaries, which are more likely to experience multiple stressors and high spatial and temporal variability in pH, pCO_2, and alkalinity. Controlled laboratory, mesocosm, and/or field experiments on multi-species assemblages are required to provide the empirical data necessary to grasp the impact of these multiple factors on complex marine ecosystems. Such studies are also required to parameterize mathematical models of ecosystem behavior that will permit examination of interactions with the physical environment and prediction of future states.

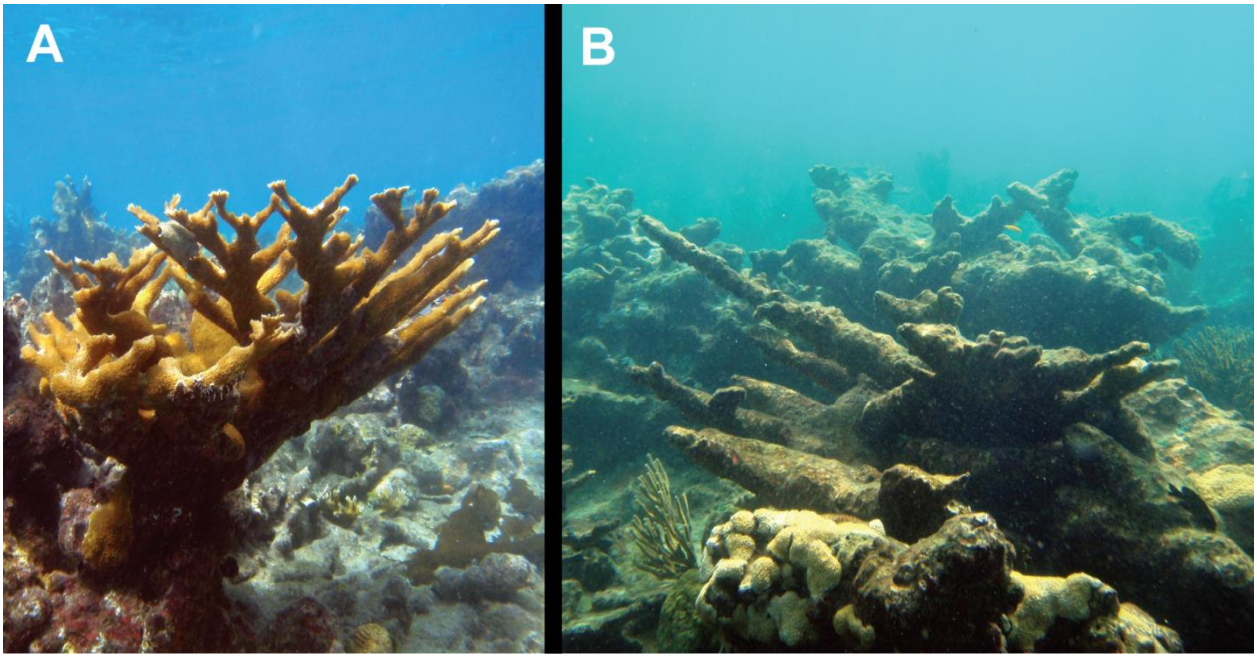


Figure 6. Examples of A) a healthy coral reef, and B) a degraded coral reef. Ocean acidification will contribute to such degradation on many coral reefs world-wide in the coming decades. Figure from Moyer, 2009; photo credit: R.P. Moyer.

Environmental and Ecological Responses and Indices

Key pathways and transformations of ocean carbon and nutrient cycles will likely be affected by ocean acidification. Increased CO_2 and decreased pH in seawater are expected to affect the chemical speciation of nutrients and trace metals, which are needed in bioavailable forms for various biochemical processes inside cells. Research suggests the latter will alter phytoplankton abundance and community structure (Huesemann *et al.* 2002, Millero *et al.* 2009), creating an interactive feedback cycle. Although rates of carbonate sediment dissolution are slow, they will increase as waters become more acidic. These changes may not only alleviate changes in seawater pH and carbonate saturation state imposed by rising pCO_2, but they may also affect the rate and amount of atmospheric CO_2 absorbed by the oceans.

Given the complexity of ecosystems, indices need to be developed that capture their current status and trajectory without having to monitor the status of every component of an ecosystem.

Such indices would expect to reveal shifts in future states and so aid in the employment of mitigation and adaptation strategies. In an effort to identify these "early warning" indicators, research efforts need to focus on choosing both relevant species and geographic sites (next section, this Theme) for intensive long-term monitoring (see Theme 1). Established sites (e.g., LTERs, Marine Sanctuaries, ocean time-series locations; refer to Boxes 1-2 for examples) and well-studied species (e.g., pteropods, certain coral species, and certain larval species) will be important for initial efforts; however, these may not be the most appropriate sites/species for detecting the full impact of ocean acidification. Laboratory dose-response studies should be integrated with monitored field parameters to identify useful biological indicators of ocean acidification and its effects. Once indices are identified and accepted as bellwether indicators, activities can pass into a monitoring mode.

Understanding Earth History to Inform Ocean Acidification Predictions

The geological record provides a series of natural experiments that show environmental and biological responses to carbon cycle perturbations of the past, including ocean acidification "events," that have been equal to or greater in magnitude than that observed in the modern instrumental record. Understanding these ancient events is important because it is not certain that changes observed under modern conditions (including controlled experimental results) can be extrapolated to the century-plus timescale. Paleoecological and geochemical research priorities should include: developing and refining proxies of ocean pH and carbonate saturation state; determining the timescales under which carbon is removed from the ocean-atmosphere system by natural sequestration; defining the background state of carbonate chemistry (baseline) in the modern and ancient ocean; determining the timescales and amplitudes of past ocean acidification events; and determining how organisms and ecosystems responded to and recovered from past ocean acidification events. These research efforts should be used to inform ocean acidification models (Theme 3).

Laboratories and Field Sites

Shared-use ocean acidification facilities and coordinated field activities are needed for conducting appropriately controlled, manipulative experiments on individual marine species and ecological communities (NRC 2010a). An evaluation of which regions are in need of such facilities and where they might be optimally located should be conducted. The development of: "ocean acidification facilities for high-quality carbonate chemistry measurements, Free Ocean CO_2 Experiment (FOCE) sites, mesocosm facilities, wet labs with well-controlled carbonate chemistry systems, facilities at natural analogue sites, and inter-comparison studies to enable integration of data from different investigators" is critical to ensure the success of future ocean acidification research (NRC 2010). It is also recognized that experimental facilities will have important chemical analytical needs, the technology for which should be co-located at the experimental facilities especially for sample types which cannot be preserved. Such facilities are needed to allow researchers to mimic natural patterns of variation in the environment, test species responses to ocean acidification, and to allow statistically defensible replication of experiments. Some Federal and academic experimental facilities have been established or are currently being developed (Box 2), but other locations will be required. An inventory of existing and planned Federal and non-federal ocean acidification facilities is strongly advised as a valuable resource for scientists studying the impact of ocean acidification.

Box 2. Examples of Federal and academic experimental facilities suitable for ocean acidification research.

Facility	Location
Bodega Marine Laboratory	University of California; Davis, CA
EPA National Health and Environmental Effects Research Laboratory	Gulf Breeze, FL, Narragansett, RI, and Newport, OR
Friday Harbor Laboratories	University of Washington; Friday Harbor, WA
NOAA Alaska Fisheries Science Center	Kodiak and Juneau, AK and Newport, OR
NOAA Northeast Fisheries Science Center	Highlands, NJ and Milford, CT
NOAA Northwest Fisheries Science Center	Seattle, WA
Ocean Acidification Research Center	University of Alaska; Fairbanks, AK
USGS Saint Petersburg Coastal & Marine Science Center	Saint Petersburg, FL

In addition to laboratory and mesocosm facilities, technology to perform ocean experiments *in situ* should be further planned and implemented. Development of the technology to perform experiments with CO_2 in the ocean is underway at the Monterey Bay Aquarium Research Institute (MBARI), as part of the FOCE system (http://www.mbari.org/highCO2/foce/home.htm). Field-based process studies on the impacts of ocean acidification on coral reefs are also currently being conducted by a consortium of researchers from NOAA, USGS, University of Puerto Rico, and Columbia University at the Atlantic Ocean Acidification Test-Bed in La Parguera, Puerto Rico.

To understand how ocean acidification is and will be affecting U.S. coastal resources, it is recommended that Federal monitoring activities focus on field sites of high resource value. These would be chosen to be part of a suite of ocean acidification intensively studied marine areas (OA-ISMAs) which are known to be in vulnerable geographic areas. Existing protected areas, monitoring sites, and laboratories co-located with field sites should be included in this effort as appropriate (refer to Boxes 1-3 for examples). A list of potential long-term field sites should be generated for the highly characterized geographic regions along the U.S. coasts and a subset selected for targeted ocean acidification monitoring and experimental work. Representative sites should also be identified for each major large marine ecosystem with initial foci on coral reefs and higher latitude systems (e.g., Alaska and the Pacific Northwest). Sites should be in close proximity to observing systems with capacity to characterize the carbonate status of the system. Within these field sites, organisms likely to represent “ecosystem health” should be chosen for monitoring for long-term changes in health and abundance. Developing this list will require additional research on individual species. These sites may be appropriate for on-site CO_2 manipulative experiments, similar to FOCE and Submersible Habitat for Analyzing Reef Quality (SHARQ, Yates and Halley 2003; See Theme 4, Box 6) experiments conducted in coral reef ecosystems.

Support for Data Synthesis

As the body of observations and data analysis tools derived from the ocean acidification monitoring, research, and modeling activities grows, it will be desirable to conduct periodic synthesis activities. The goal of such syntheses will be to generate readily intelligible information products, such as electronic ocean atlases, that capture the current state of understanding of acidification and its impacts on biogeochemical cycles, organisms, ecosystems, and human activities. A benefit of these analyses will be the identification of weaknesses and gaps that become apparent only after detailed information on the variability of fields has been observed.

Box 3. Examples of initiatives already in place that provide opportunities for long-term ocean acidification research.

The U.S. has a national system of marine protected areas (MPAs) that includes MPA sites, networks, and systems established and managed by Federal, State, territorial, and/or local governments that collectively enhance conservation of the nation's natural and cultural marine heritage, and represent its diverse ecosystems and resources. The national system sites work together at the regional and national levels to achieve common conservation objectives. The national system is administered through the National MPA Center within NOAA; however, each national system MPA continues to be independently managed by its respective entity or entities.

With their place-based focus, long-term data sets, and controlled activities, MPAs are ideal control areas or "sentinel sites" for examining climate change and other impacts including ocean acidification. Real-time results from monitoring programs; advice and feedback from stakeholders; and long-term synthesized information from condition reports all feed into decision-making for an MPA.

The national system partners are currently working to establish a linkage between the national system of MPAs and IOOS. Ocean acidification research and monitoring teams should coordinate through the MPA Center to bring the national system of MPAs into the network of OA-ISMAs especially where investments in monitoring and research have already been made.

In addition to those initiatives, NSF has a program to fund Long-Term Ecological Research (LTER, http://www.lternet.edu/) established in 1980. There are 26 LTER sites representing diverse ecosystems and research emphases and involving more than 1,800 researchers. This program provides ideal opportunities for investigation of long-term impacts of ocean acidification on important marine ecosystems. Moreover, time-series observation sites, such as the Hawaii Ocean Time-series (HOT) and the Bermuda Atlantic Time-series (BATS) study sites, have been documenting the process of ocean acidification for more than 20 years through NSF and NOAA funding.

The Atlantic Ocean Acidification test-bed (AOAT) is a nexus of *in situ* research activities that have focused on the impacts of ocean acidification to Atlantic coral reef ecosystems since 2008. A core component of the AOAT is using autonomous measurements of carbon system parameters (see Theme 1) to inform process-based field studies of coral reef ecosystem response (e.g. net calcification, photosynthesis, respiration, benthic community structure) to temporal changes (diurnal, seasonal, annual) in ambient carbonate chemistry. The project unites an interdisciplinary team of investigators from NOAA, USGS, University of Miami, Columbia University, Woods Hole Oceanographic Institution, and the University of Puerto Rico-Mayagüez. Primary funding is provided by the NOAA CRCP.

Goals

Research efforts coordinated by the National Ocean Acidification Program should build upon existing research programs, as well as ongoing biological and chemical monitoring efforts, to determine physiological responses of marine organisms, examine impacts on marine food webs, and develop indices that track marine ecosystem responses. Research efforts will ultimately enable more comprehensive modeling efforts and facilitate development of appropriate mitigation and adaptation measures. Although specific short- and long-term research priorities are delineated below, it is difficult to assign these topics to timelines as many of the long-term research goals will require work in the short term as well. Most of the research goals listed below are receiving some attention already. The short-term goals address issues that could be resolved quickly with adequate funding. The long-term goals should also be addressed as soon as possible, but they may take longer to yield their full benefits and/or require completion of one or more short-term goals.

Short-term (3-5 years)

- Identify gaps in laboratory and field-site facilities necessary to conduct ocean acidification experiments, and develop appropriate new facilities.
- Conduct research to identify potential field sites and candidate species for long-term ecosystem-level monitoring, and subsequently develop and increase their capacity for long-term, ecosystem-level monitoring (in conjunction with efforts described in Theme 1).
- Quantify changes in physiological processes in marine calcifying organisms caused by ocean acidification and its interaction with other stressors, giving priority to:
    - Key commercial species;
    - Key components of oceanic food chains;
    - Key ecologically-important species (e.g., reef-building organisms); and
    - Under-studied groups with special need for attention (e.g., cold-water corals).
- Quantify changes in physiological processes on a diversity of marine non-calcifying organisms caused by ocean acidification and its interaction with other stressors, with emphasis on establishing baseline data for key species, including:
    - Bacteria;
    - Primary producers (e.g., macroalgae, phytoplankton, and seagrasses);
    - Invertebrates (e.g., squid, tunicates, and jellies); and
    - Fish and other vertebrates.
- Develop a candidate list of organisms that can serve as marine ecosystem “sentinels” for early warning purposes and develop standard operating procedures (SOPs) for their long-term monitoring (in conjunction with efforts described in Theme 1).
- Encourage modelers and data collectors to work together, determine appropriate modeling efforts, and coordinate with data collection efforts.
- Encourage studies focusing on more vulnerable ecosystems (e.g., coral reefs, high-latitude oceanic environments, and coastal environments), including those affected by multiple anthropogenic and environmental stressors.
- Encourage and facilitate international research activities (in conjunction with efforts described in Theme 6).
- Evaluate biogeochemical proxies of ocean acidification and organism response, with emphasis on calibration and multiple-proxy techniques.

- Collect and evaluate historical records (i.e., core-based studies) of organism and ecosystem response to historical changes in ocean chemistry using a combination of paleoecological and geochemical proxy techniques.
- Continue ongoing investigations of the effects of CO_2- and pH-driven changes on the transfer of carbon from the surface ocean to its depths (i.e., the biological pump).
- Continue ongoing investigations to determine how ocean acidification may alter the nitrogen, iron, phosphorous, silicate, oxygen, and sulfur cycles and their interactions with marine ecosystems.
- Predict how the rates of carbonate sediment dissolution may change in response to water column chemical changes and how this will affect water carbonate chemistry.

Long-term (10 years)

- Continue progress from the short-term goals.
- Ensure that research addresses knowledge gaps related to more vulnerable systems (e.g., coral reefs, high-latitude oceanic environments, and coastal environments, including estuaries).
- Build an understanding of why organisms respond differently to ocean acidification with respect to:
    - Physiology and response mechanisms;
    - Mineralogy of calcifying species; and
    - Gene expression.
- Investigate the potential for physiological acclimation and examine evolutionary mechanisms for adaptation to maintain or increase ecosystem resilience, with emphasis on ecologically and economically important organisms.
- Investigate how changes at the organism level will alter ecosystem structure and function using techniques that include evolutionary genetics, laboratory, field, and mesocosm experiments on single and multi-species assemblages.
- Investigate cumulative or synergistic effects of ocean acidification with other stressors, including increased ocean temperatures and eutrophication.

Budget

The President's FY 2012 Budget proposed $14.43 million to support research efforts under the National Ocean Acidification Program, as described above in Theme 2 (see Appendix 2 for more details). Agencies presently supporting ocean acidification research efforts include NASA, NOAA, NSF, and USGS. Additionally, other Federal agencies have indirect activities that could easily be enhanced to provide data that could prove incredibly valuable to ocean acidification researchers.

Theme 3. Modeling to Predict Changes in the Ocean Carbon Cycle and Impacts on Marine Ecosystems and Organisms

Ocean modeling has progressed rapidly during recent decades with the inclusion of biogeochemical models embedded in three-dimensional general circulation models. The biogeochemistry ocean general circulation model (BOGCM) community has progressed towards simulations of the global carbon cycle, and ultimately towards a predictive capacity that includes changes in the carbon cycle as a function of changes in global temperature, ocean circulation, ocean biogeochemistry, and terrestrial and atmospheric inputs. For instance, Steinacher *et al.* (2009) realistically represented saturation states of DIC (Ω_{DIC})and aragonite (Ω_{arag}), a mineral phase of calcium carbonate, for the surface global ocean, and then projected those parameters forward for the Arctic in 2100 (Box 4). The BOGCM community has made strong progress towards incorporating aspects of the carbonate cycle into modeling frameworks and continues to improve its ability to realistically capture experimental results within models.

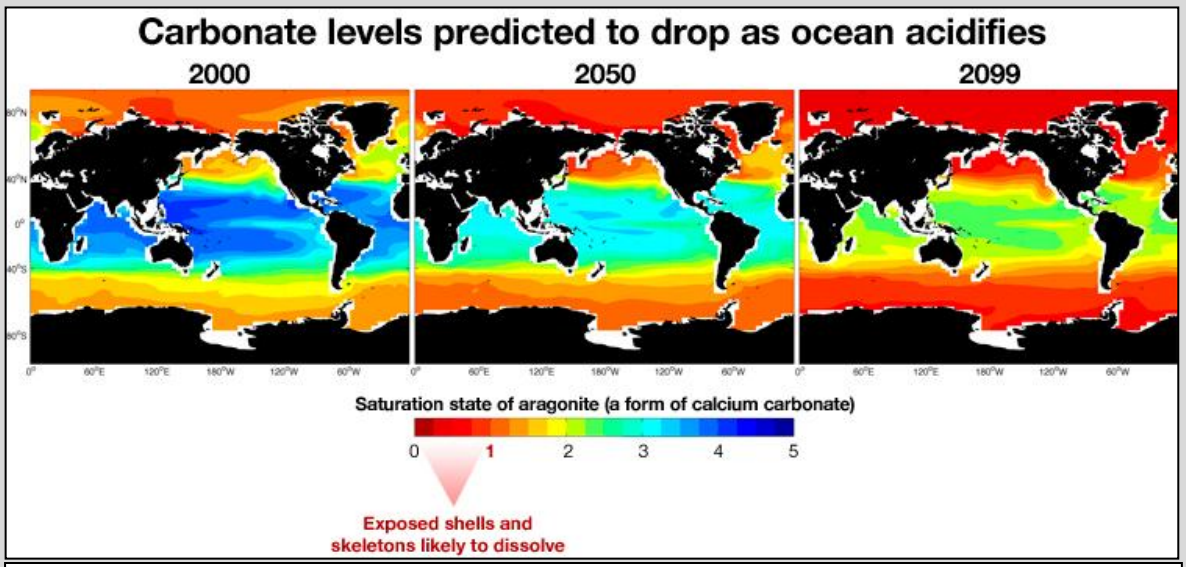
In contrast, the incorporation of realistic biological ocean properties, conditions, and parameters into BOGCMs to examine ocean acidification is still in the very early stages, which largely reflects the broader state of the field rather than solely the status for ocean acidification. At this point, scientific understanding of the responses of organisms to ocean acidification is limited (Theme 2), making it difficult to understand and model organismal response to an acidifying ocean. New approaches such as trait-based modeling that permit exploration of the capacity of entire communities of species to adapt to environmental change (e.g., Follows *et al.* 2007) or individual-based models (IBMs) that have explicit descriptions of species behavior, have strong potential for ocean acidification modeling. Ultimately, these issues are not specific to ocean modeling, but to all attempts to capture ecosystem complexity in a computer model and then project how the system will respond (e.g., Gilman *et al.* 2010).

There is a need for models that can provide for ocean resource management and decision support by addressing acclimation and adaptation issues, including habitat shifts and invasions at both global and regional levels. Regional models are especially needed for high-latitude open-oceans, coral reefs, and coastal regions, which are all vulnerable to ocean acidification in the near-term. Considerable progress is required to reach this level of accuracy because decision support often requires shorter time- and spatial-scales (e.g., shorter data latency) than many current three-dimensional models can realistically provide. Some types of decision support can best be provided by empirical models (i.e., regression) rather than by utilizing Regional Ocean Modeling Systems (ROMS), which have a more limited spatial domain than BOGCMs but lack the necessary operational capability for management and decision support. Empirical models, however, are ineffective for extrapolations beyond a few days, and they lack the capability to provide new insights for ecological interactions or climate alterations. There is a general need for developing adequate regional models such as ROMS or Finite Volume Community Ocean Models (FVCOMs) that are nested within, or use output from BOGCMs, in order to manage a variable and changing climate and for human adaptation to climate change. Investment in this area of modeling in the near future is a necessity to understand these complex, intersecting systems. Similarly, there is strong interest in Integrated Assessment Models (IAMs) that are primarily econometric (Theme 5), but have increasingly included ecological components to

capture the interaction between ecosystems and economics (Box 5). Such models have not yet been applied to ocean acidification impacts on coastal economies.

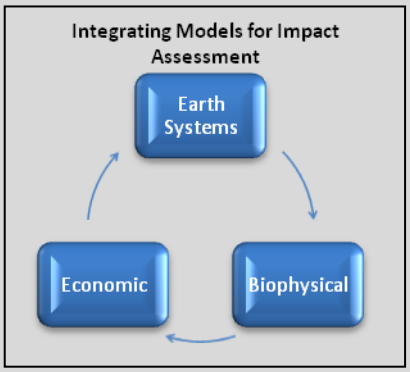
Box 4. Global carbonate modeling

Aragonite is a form of calcium carbonate ($CaCO_3$) used by organisms such as calcifying algae, bivalves, corals, and foraminifera to produce shells and other structures. Under the Intergovernmental Panel on Climate Change (IPCC) emission scenario A2 (Metz *et al.* 2007), global surface waters currently suitable for calcification by aragonitic organisms will disappear in the Arctic by 2070, coinciding with a pH decrease of 0.45 (Steinacher *et al.* 2009), which would lead to widespread aragonite undersaturation (Ω_{arag} values less than 1). Under the scenario in which the world chooses consistently and effectively a development path that favors efficiency of resource use and "dematerialization" of economic activities (IPCC scenario B1), the mean Ω_{arag} of surface waters will still likely decrease from 3.4 (pre-industrial level) to 2.3 by the end of the century. The authors highlighted several model deficiencies such as the lack of feedback between carbonate state variables and the biological carbon cycle (Steinacher *et al.* 2009). Feeley *et al.* (2009) also modeled global aragonite saturation, and their results predict that only tropical and subtropical waters will be able to support growth of calcifying organisms by the end of the 21st Century. A subset of their results are depicted below:



Model-calculated aragonite saturation states throughout the surface ocean in 2000, 2050, and 2099 (From *Oceanus*, January 2010; adapted for *Oceanus* from Feely *et al.* 2009; designed by Katherine Joyce, Woods Hole Oceanographic Institution). Surface values were calculated with the National Center for Atmospheric Research's Community Climate System Model 3.1. Most exposed aragonite structures (corals, shells, etc.) will dissolve in regions where the aragonite saturation state is below 1 (shades of red). Growth of calcifying organisms may decrease with declining saturation state, even if it remains above 1 (Doney *et al.* 2009, Feely *et al.* 2009).

Box 5. Integrated Assessment Modeling



Integrated assessment models (IAMs) link models of different systems to assess how changes in one of the modeled systems are likely to affect outcomes in one or more of the linked systems. The most prevalent examples of IAMs are those that assess the socioeconomic impacts of climate change. Climate IAMs link one output of economic activity, greenhouse gas emissions, to Earth systems models that represent the atmospheric dynamics that ultimately contribute to climate change. Changes in the Earth's climate will impact things like food production, human health, and sea level rise. An economic model then operates on the outcome of these processes to forecast changes in social welfare and economic productivity which, in turn, influences the emissions of greenhouse gases. Thus the linking of dynamic models from different academic disciplines can provide valuable insight to policy makers. An analogous IAM for the causes and consequences of ocean acidification will require linking models of the atmospheric, terrestrial, and ocean carbon cycles, the biophysical processes by which changes in temperature and ocean chemistry affect the flow of marine ecosystem services, and, finally, an economic model that determines how social welfare and economic productivity are expected to change as a result.

Requirements and Recommendations

Recommendations are based on the NRC Report (2010a), Oschlies *et al.* (2010), and Fabry *et al.* (2008). There is a general need to for more integration of biogeochemical models with ecosystem/food web models via mechanistic relationships. Progress has already been made in merging these two classes of models with programs such as Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) making it a focus area, but further efforts are needed to understand the utility of the various approaches.

Recommendations for modeling with respect to ocean acidification include:

- Develop physiology-based models that describe organismal response to ocean acidification and extend beyond single parameter response (e.g., calcification) to include growth and reproductive success.
- Target specific keystone or economic species. Increased efforts to examine effects of ocean acidification on individual species should focus on keystone or economic species in different ecosystems. Clearly, managing various fisheries species specifically sensitive to an acidifying ocean, including bivalves, crustaceans, and fish, will require an understanding of ocean acidification effects (Theme 2), which will need to be captured in models to determine potential ecological and socioeconomic impacts and support resource managers.
- Incorporate more detailed life history strategies of specific organisms at higher trophic levels. In most BOGCMs, zooplankton are the highest trophic level, whereas in fisheries models, they are the lowest, making zooplankton a crucial link. Although knowledge and parameterization of zooplankton and larval fish sensitivity to ocean acidification is limited, and end-to-end food web modeling is still a nascent field, improved ability to capture these aspects is critical for projecting effects of ocean acidification on ocean ecology.
- Develop an understanding of the interactions between ocean acidification, oxygen concentration, atmospheric inputs, and temperature, which are all affected by climate change.

This is needed for all of the oceans, but it is compelling for the Pacific and Arctic Oceans, which are already experiencing large increases in temperature and diminished aragonite saturation due to ocean acidification.

- Incorporate improved representations of remineralization processes, especially in the depth zone just beneath the surface, sunlit layer (the "twilight zone"). This will also require connecting "ballast" export flux and organism biology, because particle size and composition and trophic interactions affect the sinking speed and extent of remineralization in the water column.
- Refine and select appropriate parameterizations for PIC and couple it with carbonate chemistry, rather than treating them independently.
- Use alkalinity as prognostic tracer rather than diagnostic from salinity. Alkalinity is a key component of the carbonate system, but models often calculate it as a constant function of salinity. It should be directly calculated so that its effect on organisms can be accurately defined.
- Address needs specific to estuaries and coastal regions, including:
    - Develop an increased capacity for regional downscaling to study regional effects of global forcings. Climate forecasts are necessarily done at the global scale, but modeling local environments that contain specific ecology and conditions (e.g., coral reefs, nearshore habitats, the Arctic and Southern Oceans) requires coupling global drivers to the regional grid-scale.
    - Use high-resolution regional models to realistically represent coastal upwelling or coral reef hydrodynamics that are smaller than the grid-scale of global models.
    - Couple current sophisticated terrestrial land-use-land-use-change (LULUC) models with coastal hydrology to provide critical information for regions where most of the populations resides. Currently, coastal models often include only crude representations of river inputs or estuarine circulation, thus limiting our ability to understand the influence of terrestrial forcing from land use changes or to capture important benthic-pelagic coupling in shallow ecosystems.
      Develop IAMs and other appropriate food web and ecosystem models to forecast impacts of ocean acidification on coastal fisheries and economies.
    - Develop models that will differentiate natural and anthropogenic CO_2 sources (i.e., atmospheric CO_2 and respiration-derived CO_2 from human-induced eutrophication).

Overarching recommendations for improving the overall modeling endeavor include:

- Use models to guide observational sampling strategies (Themes 1 and 2). Observing System Simulation Experiments (OSSEs) are widely used in some fields to plan the most effective and efficient design for sampling, but they have scarcely been applied to marine science.
- Adequately archive model code (addressed in Theme 7).
- Document model skill assessment (evaluation metrics) in modeling reports.

Goals

The incorporation of realistic biological parameters into global ocean models and development of regional and coastal models are essential to understanding and planning for the effects of ocean acidification on ecosystems and human society. Many of the ocean acidification modeling

goals listed below are receiving some attention already. The short-term goals address issues that could be resolved quickly with adequate funding. The long-term goals should also be addressed as soon as possible, but they may take longer to yield their full benefits and/or require completion of one or more short-term goals. Many modeling goals are limited by the availability of experimental results that will arise from the other themes of this strategic plan. With that caveat, and awareness of tremendous amounts of ongoing efforts worldwide to provide the relevant understanding, the goals are:

Short-term (3-5 years)

- Develop and improve models less complex than end-to-end models that can predict direct and indirect effects on economically and ecologically important species and processes;
- Strengthen ocean biology life history and trophic couplings in end-to-end models;
- Explore use of OSSEs for *in situ* and remote/satellite and aircraft-based ocean acidification observation network design;
- Continue progress on nesting downscaled regional models within global climate models to ensure an understanding and predictive capability of the impact of a variable and changing climate on ocean biology (adaptation); and
- Expand implementation of alkalinity as a tracer and incorporation of PIC and remineralization formulations in BOGCMs.

Long-term (10 years)

- Continue progress from the short-term goals, and revise near-term priorities as needed based on progress;
- Invest in and develop multi- and interdisciplinary models to ensure coupling of coastal processes on both sides of the land-ocean boundary, as well as atmospheric processes;
- Ensure adequate Federal capacity for archiving model code and results (in conjunction with efforts described in Theme 7) to support management and decision making; and
- Develop appropriate decision support tools for use by regional and local resource managers.

Budget

The President's FY 2012 Budget proposed $3.07 million to support biological, chemical, and physical modeling efforts for the National Ocean Acidification Program, as described above in Theme 3 (see Appendix 2 for more details). Agencies presently supporting ocean acidification modeling efforts include NASA, NOAA, NSF, and USGS.

Theme 4. Technology Development and Standardization of Measurements

A key component of any scientific program is the ability to measure all of the required parameters while ensuring adequate data quality. This is particularly true for ocean acidification research, which is rapidly developing into a multidisciplinary program with many facets. Adequate documentation and archival storage of the measurements is also a fundamental requirement (see Theme 7).

Numerous studies have been performed to qualify and quantify the effects of ocean acidification on marine organisms and ecosystems, but some contradictory conclusions have been reported due to, among other factors, the use of different sampling and experimental protocols. Improved spatial and temporal sampling is needed to increase statistical power and detect biologically meaningful effects; to maximize the likelihood that non-significant results are really a reflection of no biological effect; and to minimize the likelihood that such results are caused by insufficient replication for the levels of variation present in the experimental system (Havenhand and Schlegel 2009). The numerous variables affecting experiment conclusions increase the difficulty of producing reliable results. In many cases, long-term experiments under highly monitored conditions must be performed to correctly attribute changes in organism health to ocean acidification. For example, carbonate chemistry shows significant diurnal and seasonal changes (Kleypas *et al.* 2006), emphasizing the need to establish an adequate baseline to predict changes due to ocean acidification. Some factors that might affect experimental results are temperature, nutrient availability, light abundance, and distinct individual responses owing to changes in species interaction. Other factors that may result in misleading conclusions are inappropriate experimental protocols, misinterpretation of data, and inconsistent model parameterization (Raven *et al.* 2005, Riebesell *et al.* 2010).

A deficiency in most ocean research is specific instrumentation for continuous autonomous monitoring *in situ*. This holds true specifically for the measurement of inorganic carbon species impacting the ocean biota, but also for the bulk and specific indicators of ecological response. For example, while autonomous measurement capabilities for pH and pCO_2 on buoys and other platforms are commercially available, promising methods for assessing exchanges with the benthos (seafloor) over a range of depths and habitats, are still under development. If the priorities outlined in the previous sections are to be implemented, particularly the establishment of long-term monitoring sites and greatly expanded field research, the availability, affordability, and robustness of *in situ* sensors will have to be improved.

Requirements and Recommendations

Effective ocean acidification monitoring and research programs require strong technology development and measurement standardization components to improve capabilities for studying the response of organisms to rising CO_2 and changing climate. Critical efforts include: ensuring that appropriate, comparable research protocols are utilized; the development, standardization, and implementation of measurement approaches and research methods; sensor and other technology development; and establishment and maintenance of centers of expertise and community research facilities.

Several recent planning documents and workshop reports have strongly promoted the development of standardized approaches and new instrumentation for ocean acidification research (e.g., Kleypas *et al.* 2006, Fabry *et al.* 2008, Borges *et al.* 2010), and this strategic research plan supports use of these recommendations.

Issues perceived by the scientific community as key to enabling comparability among results include (Orr *et al.* 2009, Riebesell *et al.* 2010):

- Use of appropriate pH measurement protocols and pH scale (recommendations and methods can be found in Riebesell *et al.* 2010, and references therein).
- Use of adequate methods to manipulate and measure carbonate chemistry during experiments (recommendations and methods can be found in Riebesell *et al.* 2010, and references therein).
- New method development for less expensive and lower sample volume measurements of DIC and TA, as well as for proxies that may indicate stress on marine biota.
- Use of pCO_2 and pH values in models that reflect realistic levels of ocean acidification relevant for the coming century. Values of pCO_2 exceeding realistic ranges can follow or be coupled with realistic values, but they should not be used as sole study values.
- Properly maintaining and slowly acclimating organisms to the stressor agent. Protocols to properly maintain sensitive species in the laboratory need to be developed.
- Monitoring all major variables affecting overall organism response to ocean acidification. Environmental factors affecting organism response, such as temperature, light, nutrients, and dissolved oxygen, should be monitored in addition to carbonate system parameters.
- Designing experiments to maximize statistical power. Observations should be reproducible, experiments should be repeated whenever possible, and treatments should be replicated.
- Use of statistically informative multivariate techniques might be necessary in experiments that measure multiple response variables.

Research Protocols

The best methods for discrete and underway measurements of the inorganic carbon system are well established and described in great detail in the *Guide to Best Practices for Ocean CO_2 Measurements* (Dickson *et al.* 2007; Figure 7). Similarly, the World Ocean Circulation Experiment (WOCE) Manual for hydrographic measurements, including dissolved oxygen and nutrients, was recently updated to reflect the current state of the science (http://www.go-ship.org/HydroMan.html). Other programs have also developed standard methods for various relevant biological measurements. Finally, the European Union project, European Project on Ocean Acidification (EPOCA), has recently published a *Guide to Best Practices for Ocean Acidification Research and Data Reporting* (Riebesell *et al.* 2010; Figure 7) that builds on the Dickson *et al.* (2007) guide with specific recommendations for ocean acidification studies. Both of these documents were developed and reviewed by a broad international group of scientific experts and should be followed whenever possible.

Figure 7. *Guide to Best Practices for Ocean CO_2 Measurements* (Dickson *et al.* 2007) and *Guide to Best Practices for Ocean Acidification Research and Data Reporting* (Riebesell *et al.* 2010).

In addition to the recommendations put forth by these guides, inorganic carbon Certified Reference Materials (CRMs) are available from the laboratory of A. Dickson (Scripps Institution of Oceanography) for verifying that DIC and TA measurements are consistent with an agreed upon international standard (http://andrew.ucsd.edu/co2qc/index.html). These verification procedures are essential for ensuring that measurements made by the growing community of ocean acidification researchers are accurate and comparable. The Dickson Laboratory is also preparing limited quantities of high ionic strength buffers that will be available to help calibrate pH measurements in seawater. Reference materials are also being developed for inorganic nutrients. The use of CRMs is critical for ocean carbon cycle science and will be equally important for ocean acidification research. Funding for the production of these CRMs, work to certify these reference materials for additional carbon parameters, and expanded production of pH buffers must be ensured for the success of the ocean carbon and ocean acidification programs. Steps should be taken to ensure that the CRM program is not reliant on one investigator who must apply for research funding every few years.

Since there will certainly be many laboratories making chemical measurements as part of their ocean acidification studies, it is important that each one properly documents its procedures for ensuring the accuracy of their measurements. As stated in the best practice guide's chapter on the carbon dioxide system in seawater, "Additional efforts are required to document procedures effectively and to establish a community-wide quality assurance scheme for each technique" (Dickson *et al.* 2007). Such a scheme will necessitate that each laboratory achieve the following:

- Writing appropriate SOPs for the techniques they are using.
- Using inter-laboratory comparison exercises to assess the various figures of merit for each method (accuracy and precision).

- Regular use of certified reference materials to assist in the quality control.
- Regular laboratory performance testing using blind samples.
- Working collaboratively to ensure that high-quality standards are available to the scientific community.

It should be noted that the ocean acidification best practices are an evolving activity. Thus, financial support for guide updates and methods development/assessment working groups will continue to be essential. A full understanding of ocean acidification will require biological and chemical measurements that include much more than the inorganic carbon system. As relevant measurements are explored and appropriate techniques developed, the community will need to be informed of the latest state-of-the-art in ocean acidification measurement approaches and techniques.

Procedures should be put in place to ensure that proposals funded through the ocean acidification program will follow the guidelines and quality assurance/quality control (QA/QC) procedures discussed above.

Measurement Approaches

Oceanographers currently use a variety of tools to observe the ocean (Theme 1). These include satellite observations, shipboard sampling programs, and autonomous *in situ* instruments. All of these approaches are employed to varying degrees for ocean acidification research. One common aspect of all the ocean acidification research themes is the need to characterize the inorganic carbon system. Methods exist for discrete inorganic carbon measurements from the water column samples, but to properly address the monitoring and experimental needs outlined in this strategic research plan, a variety of approaches, including extensive use of autonomous instruments, will be required. Commercial systems are available for moored measurements of pCO_2 and pH, but this is not an ideal measurement pair as outlined in the following section on technology development (this Theme). A significant investment is needed in additional monitoring technology development to properly assess the full carbon system using unmanned platforms, including moorings, gliders, autonomous vehicles, and floats.

In some cases existing tools will need to be employed in new environments and modified appropriately. For example, baseline studies that encompass the natural temporal (diurnal to interannual) and spatial (latitudinal) changes in near-reef carbonate chemistry are underway but in limited areas (Yates and Halley 2006a, 2006b). Such baselines should be ascertained through the use of *in situ* instruments and high-frequency water samplers as well as small vessel-based water sampling at selected reefs across large latitudinal gradients. Methods have been established for measuring calcification and extension rates from cores of massive reef-building stony (scleractinian) corals (Buddemeier and Kinzie 1976, Chalker and Barnes 1990). These methods need to be applied systematically both to older massive corals and to younger branching and encrusting corals broadly distributed across gradients of aragonite saturation state. In addition, a global array of simple calcification plates (or similar devices) should be deployed to monitor the calcification rates of sessile calcareous organisms, such as crustose coralline algae, a major reef builder that often acts as the “cement” holding reefs together. There is also a need to calibrate existing ocean acidification-specific geochemical proxies (e.g., measurements of boron and

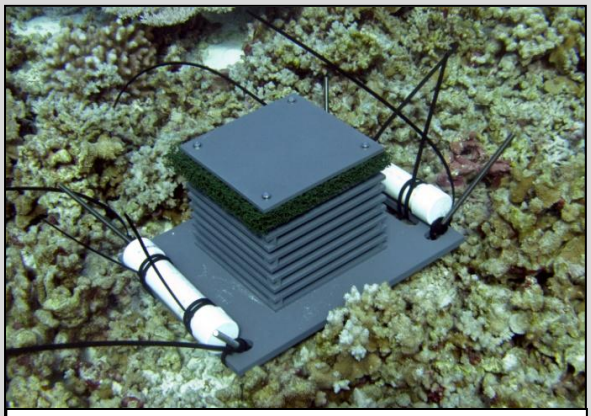
carbon isotopes) and to develop new multiple proxy techniques to complement these growth and calcification measurements.

In addition to the existing research tools, the development of new approaches to ocean acidification research is needed. For example, the coral reef projects of the Census of Marine Life have developed Autonomous Reef Monitoring Structures (ARMS) as systematic collecting devices, and they are currently developing mass parallel molecular sequencing capabilities to allow comparative and time-series analyses of indices of invertebrate biodiversity for hard-bottom habitats around the globe (Brainard *et al.* 2009, Box 6). Similar systematic collecting devices should be employed to assess biodiversity changes in soft-bottom and planktonic communities. Other cost-effective tools for monitoring biological shifts in community structure include passive Ecological Acoustic Recorders (EARs; Lammers *et al.* 2008, Sueur *et al.* 2008). These tools are only applicable if the geochemical composition of the sampled water body is well-characterized and monitored over time, so it is important to ensure that both the biology and geochemistry are monitored together.

Changes in the trophic balance of ecosystems can also be discerned by variation in the photosynthesis-to-respiration ratio, which can be observed using continuous dissolved oxygen measurements (Silverman *et al.* 2007). For critical regions, such as high latitudes and coastal areas, abundances and distributions of key taxa should be tracked with sufficient precision and resolution to detect possible shifts in relation to the changes in the geochemical parameters. There is an immediate need for such baseline data on calcifying organisms in regions that are projected to become undersaturated with respect to aragonite in the coming decades. Rapid, cost-effective technologies for quantifying abundances of targeted organisms should be a central component of an integrated ocean acidification observation network.

Box 6. Examples of Novel Approaches to *In Situ* Research

Autonomous Reef Monitoring Structures



Recently deployed Autonomous Reef Monitoring Structure (Image credit: NOAA PIFSC CRED).

The Census of Coral Reef Ecosystems (CReefs, www.creefs.org/about.html) project was established in 2006 as the coral reef component of the Census of Marine Life (CoML), a 10-year (2000-2010) international effort to examine the global diversity, distribution, and abundance of marine life. CReefs collaborators from Scripps Institution of Oceanography, the Australian Institute of Marine Science, and the NOAA Pacific Islands Fisheries Science Center (PIFSC) Coral Reef Ecosystem Division (CRED) developed Autonomous Reef Monitoring Structures (ARMS) as a tool for monitoring the invertebrate biodiversity of coral reefs. The ARMS design was intended to be relatively inexpensive, easy to build, and rugged enough for deployment into varying oceanic conditions (Brainard *et al.* 2009). An ARMS is comprised of alternating open and semi-enclosed layers that provide habitat for invertebrates after it is deployed on a coral reef. ARMS units are ultimately retrieved for analysis, and invertebrate species are then identified visually and/or using genetic techniques.

Submersible Habitat for Analyzing Reef Quality

Submersible Habitat for Analyzing Reef Quality (Image credit: K.K. Yates, USGS).

Monitoring and experimentation are required to understand the cause-and-effect relationships related to biological and chemical processes (Yates and Halley 2003), including those related to ocean acidification. The Submersible Habitat for Analyzing Reef Quality (SHARQ) is a large, portable incubation chamber designed by USGS researchers to isolate a mass of water over the underlying substrate. A flow-through analytical system enables continuous, 24-hour monitoring of water chemistry resulting from seafloor community processes (e.g., photosynthesis, respiration, and calcification). Collection of 24-hour monitoring data enables geographic comparison of reefs in terms of system functionality, and SHARQ could be used to compare effects of ocean acidification among global reef systems and other carbonate-dependent habitats. Additionally, SHARQ may be an appropriate platform for conducting *in situ* manipulative experiments to further explore laboratory results (Theme 2).

Technology Development

There is an immediate need to develop autonomous, commercial analytical systems for high frequency measurements of DIC and TA on a variety of surface platforms. Robust, low-power, inexpensive sensors also need to be developed for other autonomous subsurface platforms that are becoming available to the scientific community. Although currently there are no carbonate system sensors ready for profiling floats, the addition of commercially available oxygen sensors to the nascent or existing international monitoring programs, such as the Argo Program, would

help constrain carbon distributions through empirical relationships (e.g., Juranek *et al.* 2009) as well as directly evaluating biogeochemical changes in the ocean. There is a critical need for intensive time-series measurements from sensors and other analytical devices on moored buoys in at least some high productivity coastal and estuarine systems, as CO_2 and carbonate ion concentrations in these waters can vary substantially on timescales from hours to decades due to tides, photosynthesis and respiration, and/or fresh water inputs. Variations in calcium concentrations in these systems also affect the solubility of calcium carbonate minerals produced by mollusks (e.g., clams, oysters, and snails) and other ecologically or commercially important marine organisms. New technologies are essential to meeting these needs. To constrain the inorganic carbon parameters to the precision and accuracy necessary to assess spatial and temporal variability of ocean acidification and its impacts, TA and/or DIC measurement capabilities are required. Additionally, improved programs are needed that will attract a larger range of potential business partners and encourage significantly faster commercialization of new instruments (see Prevention, Control, and Mitigation of Harmful Algal Blooms program as a model: http://www.cop.noaa.gov/stressors/extremeevents/hab/current/PCM_08.aspx).

Although promising developmental efforts are underway, they require continued resources and field testing. Field deployments and transitioning of instrumentation from research labs to viable commercial production are often lacking in funded development efforts. In addition to new instrumentation for laboratory, ship and buoy settings, the adaptation of novel platforms such as gliders, autonomous underwater vehicles (AUVs), drifters, and autonomous surface vehicles to accommodate sensors for ocean acidification research is also desired. These efforts could benefit from a coordinated Federal approach using existing mechanisms such as the National Oceanographic Partnership Program and the NOAA Alliance for Coastal Technologies (ACT) program (e.g., 2012 Technology Evaluation: http://www.act-us.info/rft.php), as well as agency efforts such as NSF's Oceanographic Technology and Interdisciplinary Coordination (OTIC) program or the Federal Small Business Innovation Research (SBIR) programs.

Centers of Expertise and Community Research Facilities

The current analytical capacities and expertise in carbon system dynamics, as it pertains to ocean acidification, are not sufficient in most labs. Fortunately, several research labs (including some listed in Theme 2, as well as NOAA's Pacific Marine Environmental Laboratory) have acquired personnel with appropriate expertise and instrumentation to perform key measurements for ocean acidification as part of their decades-long involvement in global ocean CO_2 programs. Having these centers spread around the country will help make them more accessible and allow them to develop expertise in the ecosystem structure and issues unique to different regions. It is not practical for these labs to make all or even most of the carbon system measurements for a national ocean acidification program, but they can provide some analytical services, lead efforts to continue best practices, conduct round-robin quality assurance studies (i.e., sending samples for labs to analyze as unknowns), and train personnel in proper protocols and analysis. They can also serve as a nexus for design of perturbation studies to predict response of organisms to future anticipated CO_2 levels. These services will require specific support, but will benefit the entire ocean acidification community.

The Ocean Carbon and Biogeochemistry (OCB) Program, funded jointly by NSF, NASA, and NOAA, recently held an ocean acidification short course taught by experts in the field to educate

the broader community on available techniques, proper analytical methods, and potential pitfalls in designing ocean acidification studies. Similar training efforts will be needed for the next several years to teach biology to the chemists, chemistry to the biologists, and to generally educate the new generation of scientists on useful approaches for studying ocean acidification. This capacity-building effort will not only be helpful to scientists, but also to resource managers (e.g., marine sanctuaries, state and local water management groups) and relevant industry representatives (e.g., shellfish industry, instrument manufacturers) that are interested in learning more about ways to understand ocean acidification in their area of interest.

Ocean acidification training courses in different regions and habitats could be tailored to address the particular concerns of that area. Engagement of non-governmental organizations (NGOs) and regional or professional associations for these educational efforts should be encouraged as an avenue for reaching stakeholders (Theme 6). The involvement of local researchers and resource managers can provide the regional perspective, particularly in the ecosystem structure and local needs, to make the training courses more effective.

Some aspects of ocean acidification research (e.g., mesocosm studies) can be quite expensive to develop and will require sustained infrastructure support to maintain. The development of a few national facilities for ocean acidification research (refer to Box 2 for examples of existing and proposed facilities) in different environments should enable more efficient use of resources and ultimately result in higher quality research. For example, a large mesocosm facility that is available to ocean acidification researchers would allow a series of high-quality proposal-based studies to be performed without each individual investigator having to duplicate efforts and build new facilities from scratch. The availability of instrumentation to make basic measurements (e.g., high quality carbon measurements) would also allow better comparability between different studies performed at the facility. It is critical, as with global observations, to coordinate these national facilities with those of neighboring countries such as Canada and Mexico.

Goals

Ocean acidification measurement technologies will evolve dramatically over the next decade, and most of the goals listed below are receiving some attention already. The short-term goals address issues that could be resolved quickly with adequate funding. The long-term goals should also be addressed as soon as possible, but they may take longer to yield their full benefits and/or require completion of one or more short-term goals. A well-coordinated ocean acidification program will help ensure that advancements in technology are developed systematically and quickly spread through the community.

Short-term (3-5 years)

Some achievable, short-term goals that will address the most pressing current deficiencies are (Orr *et al.* 2009, NRC 2010a):

- Develop standardized methodology for measurement (Theme 1) of critical biological parameters specific to biological response to ocean acidification (as identified by efforts conducted under Theme 2).
- Establish validated SOPs for all geochemical parameter measurements (Themes 1 and 2). Results obtained under distinct validated protocols should be comparable.

- Ensure cross-calibration of measurement techniques.
- Develop best practices for manipulative field experiments and for studies in natural CO_2 venting sites and low pH regions (Theme 2).
- Establish a domestic and international network of ocean acidification research and monitoring groups that work together to develop new approaches for ocean acidification research (in conjunction with efforts described in Theme 6).
- Develop a program to ensure that researchers are following consistent and appropriate analytical methods with documented QA/QC procedures.
- Enhance programs that foster development and deployment of new sensor technologies needed for OA research.
- Expand inorganic CRM development and production efforts to better support the growing ocean acidification program needs.
- Facilitate the transition of newly developed technologies from research to commercial development.
- Calibrate existing and develop new geochemical proxies to facilitate paleoceanographic studies of organismal and ecosystem response to ocean acidification (Theme 2).

Long-term (10 years)

The following should be achievable within 10 years with adequate funding:

- Develop and commercialize instrumentation and techniques to improve capability to measure chemical and biological variables over space and time, including affordable autonomous sensors, more accessible and affordable high-quality instrumentation, new remote sensing, and *in situ* technologies.
- Integrate existing and new instruments for conducting carbon and biological system analyses onto a variety of platforms including autonomous surface and subsurface vehicles.
- Establish 2-4 regional centers of expertise providing routine analytical services and analytical training for the community and with infrastructure that is available for the community to come and conduct specific research studies.

These goals and priorities are likely to evolve over the next decade and as specific implementation plans are developed, but should provide a first-cut at the minimum level of support required to develop the ocean acidification program envisioned with this strategy.

Budget

The President's FY 2012 Budget proposed $2.51 million to support the technology development and measurement standardization efforts of the National Ocean Acidification Program (see Appendix 2 for more details). Agencies presently supporting ocean acidification technology development and measurement standardization efforts include NOAA, NSF, and USGS.

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

Coastal and marine environments are intricately linked with the human social system and the economic markets that have drawn on those resources to foster prosperity. Socioeconomics is the study of those human dimensions; it encompasses the interactions of society with its surroundings and the economic and social effects of choices made within society. Beyond examining the alterations in ocean chemistry that will result from increased atmospheric CO_2concentrations and the subsequent impacts on marine life, we must recognize the dependence of society on that changing marine environment and the consequences of those changes to society.

From an economic perspective, the ocean and coastal environment provide valuable goods and services. The "goods" refer to humans' consumptive use of marine resources and include crustaceans, mollusks, fish, and other organisms and items that we harvest for food and other consumer products. Some of the "services" include the cycling of carbon, maintaining biodiversity, and providing means for recreation. The human activities that rely on these goods and services are often intertwined with the social fabric of coastal communities and tribal groups. For example, commercial fishing provides income to a household, but for many such households it is also a way of life that is intertwined with how households operate, how spouses share responsibilities and generations interact, how communities are organized, and how people within those communities see their interactions with each other and the natural world. Such is the case for many people that reside, work, and recreate along our coasts.

We are just beginning to unravel the full effects of increased carbon dioxide the atmosphere and the resultant alterations in ocean chemistry and, therefore, are not yet in a position to fully understand the consequences that this process will have on our society; however, we can begin to address what range of future outcomes is possible. We know that a decrease in pH can have negative effects on some of those species dependent on calcium carbonate for building their shells or skeletons. Some of these species are directly consumed by humans, while others are part of the food web and would have dietary implications for other economically and culturally important species. A key question is: How fast will these changes occur and to what extent are humans and the affected species able to adapt? As suggested by the NRC (2010a), increasing our understanding of the effects of ocean acidification will inform discussions of climate change mitigation and adaptation, thus helping stakeholders and decision makers to respond more efficiently. Put simply, studying the socioeconomic implications of ocean acidification requires an examination of the affected populations, the timing and magnitude of the impacts, and potential responses to reduce the societal damages (NRC 2010a).

As we move forward with studying changes in the environment as a result of ocean acidification, an examination of the socioeconomic aspects must be pursued concurrently. Determining which of the physical effects are likely to have the largest socioeconomic impacts will be useful in guiding research resources to their most efficient use and will aid in developing an adaptation and mitigation strategy.

At this time, there are only a few evaluations of the social and economic effects from ocean acidification on which this strategic plan can build. An initial evaluation of the economic consequences on commercial aquaculture and harvest of mollusks in the U.S. estimates revenue declines, job losses, and some indirect economic effects (Cooley and Doney 2009). The economic impact of the loss of coral reef habitats due to ocean acidification has also been estimated (Brander *et al.* 2009). As the authors of these studies point out, a robust evaluation of the implications to society is not possible because of the uncertainty surrounding the physical impacts of ocean acidification and how humans would respond.

Requirements and Recommendations

Evidenced by the lack of peer reviewed studies on the socioeconomic impacts of ocean acidification, the current need for research in this area is vast and the directions are many. To some extent, socioeconomic research must follow research in the natural sciences; however, this should not preclude making resources available for evaluation of socioeconomic impacts while still actively supporting research in the natural sciences. Ideally, findings in one area would guide new research in the other. For example, it would be wise for natural scientists to research impacts of ocean acidification on species that are economically and culturally significant. Similarly, social scientists should study impacts that can be accurately represented with models of the biophysical system and are feasibly quantifiable. As such, communication between physical and social scientists, stakeholders, and decision makers will be critical. What follows is a list of research areas that will improve our ability to assess and mitigate the socioeconomic impacts of ocean acidification.

Inventory of Impacts

As our ability to monitor and forecast the physical impacts of ocean acidification improves, we will also be able to improve our assessment of the socioeconomic effects. The NRC (2010a) identified three key areas or sectors where the effects of ocean acidification are most likely to occur based on the current state of knowledge:

- Marine Fisheries – Impacts to commercially valuable finfish will most likely occur through the food web. A reduction in plankton species may reduce the abundance of commercial species since plankton is often a food source. Alternately, ocean acidification may affect the critical habitat for some species, such as alterations in coral and oyster reefs.
- Aquaculture – Successful hatcheries are dependent on careful control of the environment in which their stocks are grown. For saltwater species, ocean water is often pumped in and circulated as opposed to using artificial mixes. A change in the water chemistry, such as a reduction in pH, may result in less productivity of the brood stock and/or high larval mortality. Aquaculturists are interested in the probability, frequency, magnitude, and timing of the changes in chemistry so they can respond accordingly.
- Tropical Coral Reef Systems – Coral reef systems are complex and already being damaged by other anthropogenic stressors like water pollution, destructive fishing practices, and climate change. The impacts of ocean acidification on the health of corals and coralline algae will exacerbate these already clear impacts. Coral reefs provide habitat for commercial and subsistence fisheries, support tourism and recreation markets, and contribute to marine biodiversity.

Identifying Stakeholder Groups

Identifying stakeholders (business owners, coastal communities, seafood and tourism industries, tribes, etc.) is a critical step in forming a research agenda and one that requires attention throughout the decision making process. As data availability and modeling capabilities improve new stakeholders may emerge.

Economic Impact Assessment

Once the effects of ocean acidification have been identified, they should be quantified and, to the extent possible, monetized. Determining the magnitude of a given impact is important information and can be useful when evaluating policy or allocating resources. Expressing those magnitudes in monetary terms can, if done accurately, provide more useful information because the value of mitigating and adapting to some impacts can be compared directly with the costs of achieving those goals. Assessing the economic impacts of ocean acidification will require several components, including long-term forecasts of socioeconomic conditions, valuation of market and non-market impacts (Box 7), integrated assessment modeling (Box 4), social discounting, and uncertainty analysis. Such an impact assessment would then permit analysis of the cost-effectiveness of mitigation and adaptation strategies.

Box 7. Nonmarket valuation

When policy decisions affect goods and services traded in normal markets, changes in prices and incomes provide a monetary measure of the impact on social welfare. However, it is often the case that goods and services that are not traded in normal markets, but nevertheless contribute to social welfare, are also affected by policy decisions. In these cases, an accurate assessment of economic efficiency requires nonmarket valuation. There is a wide variety of approaches to nonmarket valuation, but all of them can be classified as either revealed preference or stated preference. Revealed preference methods rely on observing behavior that is complementary to the nonmarket good being valued. For example, it is possible to infer a value for the quality of an outdoor recreation site by observing how far people are willing to travel to get there compared with alternative sites. Stated preference methods can provide value estimates when it is too expensive or simply impossible to observe complementary behavior. Stated preference methods rely on surveys containing hypothetical choices that reveal the value that people place on nonmarket goods and services. While placing monetary values on environmental amenities and ecosystem services is not without controversy, without these monetary measures it is likely that valuable goods and services will instead be assigned zero value and ignored in policy discussions.

The social cost of carbon (SCC) is a measure of the economic benefit from a marginal reduction in CO_2 emissions and is used to evaluate the economic efficiency of regulations affecting CO_2 emissions (Box 8). All estimates of the SCC produced to date quantify damages from climate change but omit impacts from ocean acidification. This is a potentially large omission that leads to an underestimate of the SCC and the benefits from regulations that reduce CO_2 emissions. In order to more accurately evaluate the economic efficiency of CO_2 emissions policies, the economic losses resulting from ocean acidification must be considered alongside those of climate change.

Box 8. Interagency Working Group on Social Cost of Carbon (IWG-SCC)

In 2009 an interagency work group, led by the Council of Economic Advisors, convened with the purpose of providing a consistent set of SCC values for all executive agencies to use in economic analyses of regulations that affect CO_2 emissions. The effort relied heavily on three separate climate integrated assessment models (IAMs): FUND (Tol 2002), DICE (Nordhaus 2008), and PAGE (Hope 2006). The interagency group outlined a set of model inputs to be used in the calculations, including a range of social discount rates; a set of several long-term forecasts for population, income, and greenhouse gas emissions; and the sensitivity of the climate system to atmospheric CO_2 concentrations. Based on these inputs, the three climate IAMs were used to develop a range of SCC estimates. The technical support document for the interagency effort presents the results and a detailed accounting of the methods and assumptions; it is available at: http://www.epa.gov/oms/climate/regulations/scc-tsd.pdf.

Aggregate measures of economic impacts, such as percentage Gross Domestic Product (GDP) lost due to environmental damages, are useful summary statistics but tell only part of the story. It is also important to examine how those impacts are distributed across the affected population. There are a number of dimensions to consider when conducting distributional impacts analyses. Economic impacts of environmental damages can disproportionately affect some state, local, or tribal governments; geographic locations; or subpopulations of interest including historically disadvantaged communities. Decision makers will require this knowledge as they craft mitigation and adaptation strategies for ocean acidification.

Mitigation of Impacts[1]

The most direct way to reduce ocean acidification is to reduce the atmospheric concentration of CO_2. This requires sharp reductions in CO_2 emissions, increasing CO_2 sequestration, or both. Strategies to reduce greenhouse gas emissions have been extensively investigated under climate change discussions and can be found in various reports (e.g., EPA 2005, EPA 2006, Metz *et al.* 2007). They include establishment of regulatory standards on emission levels, financial incentives for innovative technology development, tradable permits, increasing energy efficiency, reduction of deforestation, promotion of reforestation, and shifting energy sources from fossil fuels to nuclear power supplies and renewable energy. These solutions would require an organized and committed international effort that crosses social, cultural, and political boundaries.

An alternate mitigation strategy is to reduce other marine stressors that exacerbate the impacts of ocean acidification. Coral reefs, for example, face a number of threats other than ocean acidification. Urban and agricultural runoff, sedimentation, and destructive fishing practices also threaten the long-term survival of coral reefs. Reducing other stressors to coral reefs may mitigate the cumulative impact and increase the chances for sustainable coral ecosystems; however, alternate mitigation strategies may not be available for all ocean acidification impacts and those that are will likely be of limited benefit.

[1] Here we adopt the convention that "mitigation" refers to slowing the onset of the physical impacts of ocean acidification while the term "adaptation" refers to behavioral changes that allow people to maintain a higher standard of living in the presence of those impacts.

Established long-term monitoring and research sites (Themes 1 and 2; Box 1), such as MPAs or LTERs (Box 3), should be utilized to test and monitor the efficacy and impacts of chosen ocean acidification mitigation measures. Existing partnerships between Federal agencies and other entities, such as DOI's Landscape Conservation Cooperatives (LCCs; Box 9), should be drawn upon to develop, test, and evaluate mitigation, as well as adaptation (next section, this Theme) protocols and ensure that they are appropriate for both the environmental and cultural needs of a community or region.

Box 9. Landscape Conservation Cooperatives

The U.S. Fish and Wildlife Service (FWS) and the U.S. Geological Survey (USGS) are working with a diverse group of partners to develop a national network of Landscape Conservation Cooperatives (LCCs). LCCs are applied conservation science partnerships composed of Federal agencies, states, tribes, non-governmental organizations, universities, and stakeholders within geographically defined areas. The goal of the LCCs is to provide a clear focus on climate change modeling and adaptive conservation design with solid management decision-support tools and evaluation of resource monitoring data. They will provide resource managers with adaptive conservation strategies and actions that will anticipate changes in habitat and the abundance and distribution of species. To learn more visit: http://www.fws.gov/science/shc/lcc.html

Pacific Islands Climate Change Cooperative
The Pacific Islands Climate Change Cooperative (PICCC) is a self-directed, non-regulatory conservation alliance whose purpose is to assist those who manage native species, island ecosystems, and key cultural resources in adapting their management to climate change for the continuing benefit of the people of the Pacific Islands. The PICCC is governed by a steering committee of Federal, State, private, indigenous, and non-governmental conservation organizations and academic institutions acting in partnership to fulfill the cooperative's mission, vision, and goals. In 2010, PICCC funded a series of projects that will vastly improve our understanding of how global climate change is manifesting at regional and site-specific scales. The projects are overseen by researchers at the University of Hawai'i, the Climate Foundation, and American Samoa Department of Marine and Wildlife Resources. Additional PICCC projects are being funded by the FWS, USGS, and the National Park Service. To learn more about the PICCC, visit: http://hawaiiconservation.org/piccc.asp.

Adaptation Strategies[1]

Some degree of further ocean acidification will occur regardless of how effective mitigation efforts are. Adapting to or coping with the resulting impacts will become necessary for some parts of the population and sectors of the economy. Adaptation to changing environmental conditions is not a new concept. Creating crops that are resistant to drought, disease, and pests is one example of a human system adapting to adverse environmental conditions; however, the changes we are likely to see in atmospheric and ocean chemistry present a challenge on a larger scale. An early example of adaptation to ocean acidification is the response of shellfish growers along the Pacific Coast. In recent years, several oyster hatcheries have experienced a near-complete collapse of production. A partnership between industry, academia and federal scientists led to the discovery that high CO2 (and a resulting low mineral saturation state) in the hatchery waters was causing the decline. As a result, hatcheries are now monitoring water quality conditions very closely and have developed adaptation strategies including closing the intake valves to the hatcheries when corrosive waters are detected and other manipulations of the

chemistry to reduce its corrosiveness before it reaches the growing oysters. Adaptation is a risk-management strategy that has costs and is not foolproof. The effectiveness of any specific adaptation requires consideration of the expected value of the avoided damages against the costs of implementing the adaptation strategy (Easterling *et al.* 2004, Metz *et al.* 2007). Additionally, ocean acidification adaptation strategies should, if possible, compliment strategies developed for other climate and ecosystem stressors (e.g., NOAA 2010).

Goals

Assessments of the socioeconomic impacts of ocean acidification are essential to for developing appropriate adaptation and conservation strategies; however, socioeconomic components have typically been lacking in past ocean acidification studies, and few of the goals listed below are receiving much, if any, attention already. The short-term goals address issues that could be resolved quickly with adequate funding. The long-term goals should also be addressed as soon as possible, but they may take longer to yield their full benefits and/or require completion of one or more short-term goals.

Short-term (3-5 years)

- Support a socioeconomic component in studies of the effects of ocean acidification, where appropriate.
- Encourage marine policy programs to incorporate ocean acidification and its socioeconomic impacts into their curricula and areas of study.
- Foster communication and collaboration between natural and social scientists to ensure that all researchers studying the impacts of ocean acidification are working with state-of-the-science methods and the most accurate data available.
- Conduct nonmarket valuation studies to estimate damages from anticipated impacts of ocean acidification.
- Develop integrated models that link physical, biological, and economic systems in order to estimate the economic and distributional impacts of ocean acidification.

Long-term (10 years)

- Foster communication between researchers, stakeholders, and decision makers to develop efficient mitigation and adaptation strategies (in conjunction with efforts described in Theme 6).
- Develop decision support tools to assist national, state, and local governments in developing management options and understanding their implications.
- Provide businesses and communities that will be adversely affected by ocean acidification with the information they need to develop adaptation action plans (Theme 6).
- Develop metrics to test the efficacy of adaptation and mitigation strategies.

Budget

The President's FY 2012 Budget proposed $297,000 to support socioeconomic assessments and development of conservation strategies under the National Ocean Acidification Program (see Appendix 2 for more details). Only NOAA presently supports socioeconomic research related to ocean acidification.

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

The FOARAM Act requires "Ocean Acidification Information Exchange" that would "go beyond chemical and biological measurements alone, to produce syntheses and assessments that would be accessible to and understandable by managers, policy makers, and the general public. This is an important priority for decision support, but it will require specific resources and expertise, particularly in science communication, to operate effectively" (NRC 2010a).

Progress on an ocean acidification implementation plan hinges on garnering support from key stakeholder groups. That support requires an understanding of ocean acidification that can be achieved by outreach and engagement. A report of the Ocean Acidification Task Force (OATF) recognizes both the importance and challenge of effective public outreach, stating, "Indeed, there is growing evidence that the interest in, and appreciation for, science in the United States is extremely low. If we expect our Federal legislators to provide substantive long-term support, the IWG-OA will need to consider how they can effectively improve communication about ocean acidification research and its relevance to society" (ORRAP 2010).

Requirements and Recommendations

As described in a recent NRC report *Informing an Effective Response to Climate Change*, "the nation lacks comprehensive, robust, and credible information systems to inform climate choices and evaluate their effectiveness" (NRC 2010b). Stemming from this same lack of information is a need for greater public education, outreach, and engagement on ocean acidification. The Interagency Ocean Policy Task Force (OPTF) established as one of the National Priority Objectives a need for public education on ocean acidification through formal and informal programs (OPTF 2010). By extension, an outreach and education component of the National Ocean Acidification Program that effectively informs and engages stakeholders and the general public will constitute an important component of domestic policy.

Recognizing the needs mentioned above, the OATF recommends that Federal agencies dedicate significant resources to the development of a robust and effective ocean acidification outreach effort, using domestic and international NGO, academic, government, and donor communities to foster this process. A well-funded strategy on ocean acidification will ideally address the need for and facilitation of communication and outreach, partnerships with domestic and international NGOs, and other stakeholder groups, and coordination of scientific research and dissemination of scientific information.

The main focus of the education and outreach program should be to enhance ocean acidification literacy by creating educational opportunities that engage stakeholders in an interdisciplinary and international approach to addressing ocean acidification. Secondly, the program should channel resources into coordinating activities among nations and international organizations while building international support for U.S. ocean acidification programs. An education and outreach program should serve immediate as well as future needs, yet be able to address unforeseen needs by remaining flexible in its outreach message, educational approach, and partnerships.

Ocean acidification is a high priority issue with local effects but global causes. Therefore, education and outreach must approach this significant environmental issue with a substantial international component. In particular, efforts should focus on regions with greater vulnerability to ocean acidification (e.g., polar regions and regions with a high dependency on coral reef fisheries or tourism), because the U.S. has a vested interest in assisting their understanding of and response to ocean acidification. Moreover, given that communication difficulties may arise more readily with international stakeholders, education and outreach efforts must make a concerted effort to engage an international audience.

Education and Outreach Activities

The National Ocean Acidification Program Office should take responsibility for the following education and outreach activities:

- Coordinating the design, implementation, and updates of the strategic plan for education and outreach.
- Organizing and hosting education and outreach events, both domestic and international.
- Making scientific assessments available to managers, policy makers, and the general public as useful education tools.
- Preparing materials for education and outreach events and any subsequent reports, updates, and/or publicity associated with those events.
- Developing a list of feedback metrics to measure the effectiveness of education and outreach campaigns on ocean acidification and arranging for independent reviews of the effectiveness of education and outreach activities.
- Serving as a central hub for a broad range of ocean acidification resources, including Federal non-federal, national, and international tools.
- Staying abreast of national and international events, developments, and resources on ocean acidification.
- Identifying opportunities for partnerships between U.S. agencies, international governments, NGOs, academia, and industry, including opportunities for funding.
- Producing materials on ocean acidification that are appropriate for media outlets.
- Representing the U.S education and outreach efforts at domestic and international meetings and conferences on ocean acidification.
- Designing and maintaining an education and outreach web portal.

Web Portal

The Ocean Acidification Information Exchange mandated by the FOARAM Act is required to "make information on ocean acidification developed through or utilized by the interagency ocean acidification program accessible through electronic means, including information which would be useful to policymakers, researchers, and other stakeholders in mitigating or adapting to the impacts of ocean acidification," a task that will require the creation and maintenance of an education and outreach web portal maintained by the National Ocean Acidification Program Office (see Theme 7 for details on the complementary data access portal). In an effort to support use of this portal by non-English speakers and an international audience, the web portal can be a gateway to information posted in multiple languages. The education and outreach resources and services that could be provided through a web portal include access to:

- Education and outreach materials on ocean acidification, including interactive web-based education tools and literature (e.g., scientific publications, press releases, and newspaper and

magazine articles) and link to existing tools (e.g., http://www.oceanacidification.net, http://cisanctuary.org/acidocean/, and http://www.pmel.noaa.gov/co2/).

- Updates and summaries on the latest science on ocean acidification.
- Interactive dialogue among stakeholders, the National Program Office, and world experts on ocean acidification.
- Links to ongoing domestic and international research on ocean acidification (e.g., http://www.us-ocb.org, http://www.epoca-project.eu, and http://www.imber.info/C_WG_SubGroup3.html).
- Links to data repositories for the complete suite of Federal, State, local, and international ocean acidification research and monitoring efforts (see Theme 7).
- Links to ocean acidification outreach and educational activities, such as domestic and international conferences, meetings, webinars, films, lectures, and podcasts.
- Links to educational courses and workshops on ocean acidification for various age groups (young and adult learning) and professionals (e.g., educators, NGOs, and government employees).
- Funding opportunities for governmental and non-governmental activities regarding ocean acidification (e.g., research, education, and outreach).

Engaging Stakeholders

Actively engaging ocean acidification stakeholders in the education and outreach activities will ensure better long-term success of other components of the national strategy. There are numerous stakeholder groups that will be affected by ocean acidification. Identification of key groups (Theme 5) will help focus education and outreach efforts. For example, interests for the domestic and international engagement strategies in ocean acidification are held by, but not limited to, NGOs; the fisheries, aquaculture, and seafood industry; recreational fishing and diving sectors; natural resource managers; and coastal tribes and territories.

Broadly, education and outreach will target interest groups who contribute to ocean acidification, those being impacted by ocean acidification, and those who can help to mitigate the effects of ocean acidification. In particular, populations that live in regions where oceans are particularly sensitive to ocean acidification may require more immediate engagement as audiences for education and outreach. Successful education and outreach activities also benefit from the support of those who generate the information being disseminated; involvement of scientists and NGOs will help to maintain consistent messages and efficient use of funds. Education and outreach programs should not take a limited view of stakeholder groups; audiences for engagement should include those whose future participation will be needed when anticipated changes in ocean acidification mitigation and policy take place.

Engagement activities should involve a wide array of educational opportunities that encourage interdisciplinary understanding of the impacts of ocean acidification and be open to international participation and new education and outreach opportunities when feasible.

Venues for engaging and interacting with ocean acidification education and outreach include, but are not limited to: professional and scientific meetings, workshops, policy institutes ("think tanks"), aquaria and museums, schools and universities, scientific and non-scientific publications, and the media (e.g., television, radio, newspapers, and virtual social networking

platforms). The National Ocean Acidification Program Office will take advantage of ongoing activities such as these, but, when more appropriate, should initiate engagement activities with the overall objective of education, outreach, or coordination.

Engagement of stakeholders in ocean acidification education and outreach will help to address OATF's recognized critical need for increased "collaboration between the various stakeholders." The National Ocean Acidification Program Office should coordinate efforts between NGOs, donors, government agencies, international entities, and other participants in education and outreach activities. Collaboration will benefit from the work already being done by NGOs and the fishing industry in their efforts to understand and communicate sustainability (ORRAP 2010). Moreover, engagement will benefit from being linked to ongoing education and outreach programs already underway by Federal agencies, NGOs, and the international community.

Linking to Existing Programs and Organizations

The National Ocean Acidification Program Office should take advantage of ongoing education and outreach activities (refer to Box 10 for examples). These ongoing activities include the range of initiatives on ocean acidification education programs as well as those related to marine sciences, general science, and climate change. In addition, the range of partners should include the full array of ongoing initiatives by the U.S. government, NGOs, international organizations, and other stakeholder groups when feasible.

Within the U.S. government, education and outreach materials are made available by NOAA, USGS, NSF, NASA, EPA, FWS, and National Park Service concerning climate change (e.g., http://www.education.noaa.gov/Climate/; http://www.cosee.net/; http://www.epa.gov/climatechange/kids/index.html; http://cisanctuary.org/acidocean/). Initiatives such as these could expand to address ocean acidification if they have not already. The National Ocean Acidification Program should also work in partnership with the National Ocean Council (NOC) Subcommittee on Education as ocean acidification science is closely related to several of the NOC priority objectives (such as "Resiliency and Adaptation to Climate Change and Ocean Acidification" and "Changing Conditions in the Arctic").

Fruitful partnerships will come from collaboration with NGOs, foundations, and other non-governmental organizations with ongoing outreach programs. The international component of an education and outreach engagement strategy, in particular, will benefit from linkages to established international collaborations, agreements, and organizations. These avenues include international NGOs, scientific collaborations, and non-binding agreements. The U.S. is an active participant in the leading international scientific collaboration on ocean acidification research. International science collaborations such as these, as well as official science and technology agreements between the U.S. and foreign governments, can be used to catalyze education and outreach on this environmental issue. Official foreign government collaborations between the U.S. and other nations on ocean acidification research and assessment already include initiatives via the Arctic Council's Arctic Monitoring and Assessment Program working group and the collaborative research cruises with the Canadian government and academia.

Box 10. **Examples of programs and organizations with existing education and outreach initiatives and venues for ocean acidification or greater climate change issues.**

U.S. government-led initiatives (Refer to Appendix 1 for detailed information regarding ongoing U.S. government initiatives):

- Multilateral partnerships (land-based pollution and marine debris)
- Coastal America
- U.S. Global Change Research Program (USGCRP)

U.S. government-academia partnerships:

- American Society of Limnology and Oceanography (ASLO)
- Centers for Ocean Sciences Education Excellence (COSEE)
- Climate Change Education Partnership (CCEP)
- Climate Literacy and Energy Awareness Network (CLEAN) Pathway
- Integrated Ocean Observing System (NOAA)
- Ocean Carbon and Biogeochemistry Program (OCB)
- National Parks Service Research Learning Centers
- National Estuary Program (NEP)

U.S. NGOs and other non-governmental initiatives:

- American Geophysical Union (AGU)
- American Association for the Advancement of Science (AAAS) Conference on Promoting Climate Literacy through Informal Science
- National Academy of Science
- Association of Science - Technology Centers (ASTC)
- Environmental Defense Fund
- Gordon and Betty Moore Foundation
- Natural Resources Defense Council
- The Nature Conservancy
- The Oceanography Society
- Pew Center

International NGOs:

- Conservation International
- International Union for the Conservation of Nature
- OCEANA
- World Wildlife Fund

International scientific collaborations:

- IPCC working groups on ocean acidification
- International Oceans in a High CO_2 World III International Meeting
- International Science Advisory Panel for the European Project on Ocean Acidification (EPOCA)
- Joint Integrated Marine Biogeochemistry and Ecosystem Research – Surface Ocean Lower Atmosphere Study (IMBER/SOLAS) working groups

Creating New Partnerships

Beyond linking to existing education and outreach initiatives, the National Ocean Acidification Program Office will have to forge new partnerships. The need for new partnerships will become

clear after an assessment of current efforts has highlighted successful strategies and important gaps. New partnerships and initiatives will be streamlined with ongoing efforts as to avoid redundancy and will target education and outreach messages and key audiences where gaps have been identified.

The National Ocean Acidification Program Office can play a pivotal role in uniting key partners by promoting working relationships between U.S. agencies, NGOs, academia, and private businesses throughout the world at ongoing and developing venues. New partnerships may take the form of public-private partnerships, which have proven successful at uniting public, private, and philanthropic partners to address complex, cross-cutting issues.

International partnerships may form via new initiatives that address emerging cross-cutting issues while striving to promote sustainable development on bilateral, regional, and global levels. As previously mentioned, formal science and technology agreements can unite governments in research partnerships which may serve education and outreach needs. Science and technology cooperation, in addition to grants for international cooperation, supports the establishment of science-based industries, encourages investment in national science infrastructure, education, and application of scientific standards, and it promotes international dialogue. Additionally, the National Ocean Acidification Program Office can form new international partnerships by leveraging existing relationships established through U.S. embassies, consulates, and missions. By building off of existing relationships, an international engagement strategy will have more relevant and achievable goals.

Goals

Education and outreach efforts are vital to fostering public understanding of environmental and socioeconomic impacts of ocean acidification and ensuring adequate stakeholder involvement in research and adaptation planning. Domestic and international engagement should supplement education and outreach efforts, as well as create partnerships that better enable goals from this and other themes to be achieved. The short-term goals listed below address issues that can be resolved in the next 3-5 years with adequate funding. Long-term goals are equally as important, but they may take longer to yield their full benefits and/or require completion of one or more short-term goals. Many of the following goals are already receiving some attention.

Short-term (3-5 years)

- Incorporate education and outreach functions directly into the National Ocean Acidification Program Office.
- Launch a public web portal as an education and outreach interface of the National Ocean Acidification Program (complementary to data access portal described in Theme 7).
- Design an implementation strategy for education and outreach for ocean acidification which will:
    - Identify all domestic and international stakeholders in ocean acidification for education and outreach efforts;
    - Identify additional resources and partners required for education and outreach domestic and international efforts;
    - Link to existing partners, especially those that represent high priority audiences.

    - Identify potential new partnerships, especially with partners that represent high priority audiences;
    - Solidify funding streams to foster development and maintenance of education, outreach, and engagement programs and activities.
    - Conduct a gap analysis to determine how the National Ocean Acidification Program Office will complement and progress ongoing education and outreach efforts; and
    - Facilitate ocean acidification data and information exchange amongst stakeholders (see Theme 7).
- Evaluate the effectiveness of the National Ocean Acidification Program Office's education and outreach initiatives using short-term measurable benchmarks.

Long-term (10 years)

- Review and update the education and outreach strategic plan as new information is generated, the stakeholders and donors audience changes, partnerships are formed and evolve, education and outreach messages change, and as the effectiveness of ongoing education and outreach initiatives is determined.
- Create new partnerships, especially with partners that represent high priority audiences.
- Evaluate the effectiveness the National Ocean Acidification Program Office's education and outreach initiatives using long-term measurable benchmarks.

Budget

The President's FY 2012 Budget proposed $775,000 to support education, outreach, and engagement efforts under the National Ocean Acidification Program (see Appendix 2 for more details). Agencies presently supporting ocean acidification education and outreach efforts include NASA, NSF, and USGS.

Theme 7. Data Management and Integration

The success of the National Ocean Acidification Program will depend critically on effective data management and integration. Data must be shared and integrated across disciplinary boundaries, drawing marine biological data together with oceanographic data and providing intelligible information to social scientists, planners, educators, and the general public. Data must also be shared and integrated across organizational boundaries, blending data from diverse systems that were created to address distinct mission goals. Finally, data must be shared and integrated across data management technology boundaries that currently limit the interoperability between *in situ* observations and gridded fields such as satellite products, data synthesis products, and numerical model outputs.

The strategy for data management within the National Ocean Acidification Program must fit within a context of national data policies and existing programs. It must follow the guidelines of the National Ocean Policy (OPTF 2010), which includes a goal of "nationally consistent, derived data products" and "a robust information management system to allow easy access to and transparency of data and information necessary for planning." It should strive for maximum consistency with the emerging NOAA Climate Service (NOAA 2010), which emphasizes "a long-term climate data archive and public access to data" and insists that data be made "interoperable with data [across] agencies."

Requirements and Recommendations

Strategic planning to meet the data management and integration needs of the National Ocean Acidification Program should build on lessons learned from successful data integration endeavors in related ocean research programs (Glover *et al.* 2006, NRC 2010a). Experience has shown that a data management office should be established early in the implementation of a program. We also know that to be effective the budget for data management should be about 5–10% of the total cost of the ocean acidification program, considering both hardware and competent staff. The OATF report to the ORRAP (2010) echoes these ideas asserting, "…there needs to be a permanent, national, interagency cyberinfrastructure system that ties together or stores in a few places all relevant data archives relevant to ocean acidification." In addition to establishment of a data management office, key elements of the ocean acidification data management and integration strategy are: developing and maintaining a data access framework and web portal; ensuring timely availability of data, version control, and citations to data; defining and enforcing standards for sensor information management and metadata records; identifying or creating a data archival center or centers; and supporting data synthesis and modeling efforts.

Ocean Acidification Data Management Office

Early establishment of an Ocean Acidification Data Management Office under the National Program Office would be highly desirable in order to oversee the many complex connections between institutions and data systems that will be contributing to the Program (NRC 2010a; refer to Box 11 for examples). If ocean acidification data management functions must be embedded within an existing Federally-supported data management activity due to resource limitations,

then it remains essential to employ staff members dedicated to a curatorship role for the ocean acidification data collection.

The model for integration, in order to respect the independence of data systems developed by the contributors, must be a system-of-systems outlook, such as has been articulated in numerous plans, including the U.S. IOOS Data Management and Communications (DMAC) Plan (Hankin and the DMAC Steering Committee 2005), NOAA's Global Earth Observation-Integrated Data Environment (GEO-IDE) plan (U.S. Department of Commerce 2006), the European Union's SeaDataNet (Schaap 2009), and the Global Earth Observation System of Systems GEOSS framework (Group on Earth Observations [GEO] 2005). The Ocean Acidification Data Management Office must also manage a shared data analysis environment to support community data synthesis and integration activities and a framework for model intercomparison.

Box 11. Examples of key data systems related to activities of the Ocean Acidification Data Management Office.

NOAA:

- Integrated Ocean Observing System (IOOS 2009)
- Global Earth Observation-Integrated Data Environment (GEO-IDE) integration framework (U.S. Department of Commerce 2006)
- Pacific Marine Environmental Laboratory Ocean Carbon Program Data Portal (http://www.pmel.noaa.gov/co2/map/index)
- National Oceanographic Data Center (NODC)

NSF-funded:

- Biological and Chemical Oceanography Data Management Office (BCO-DMO, http://www.bco-dmo.org/)
- Ocean Observatories Initiative CyberInfrastructure (OOI-CI, http://ci.oceanobservatories.org)

NASA:

- SeaBASS (http://seabass.gsfc.nasa.gov/) data base of *in situ* measurements related satellite fields
- Model outputs at the NASA Jet Propulsion Laboratory (JPL)

National Park Service (NPS):

- NPS Natural Resource Information Portal (NRInfo; http://nrinfo.nps.gov/)

FWS:

- National Wildlife Refuge System (NWRS) Inventory and Monitoring Program Data Management System

EPA:

- Environmental Monitoring and Assessment Program (EMAP)

USGS:

- National Water Information System Water-quality Web Services (http://qwwebservices.usgs.gov/)
- National Map (http://www.nationalmap.gov/)
- Modeling Data Network (http://www.sciencebase.gov/)

Department of Energy (DOE):

- Carbon Dioxide Information Analysis Center (http://cdiac.ornl.gov/)

Data Access Framework

Researchers require access to the relevant data in the context of their preferred tools for scientific visualization and analysis. Thus the National Ocean Acidification Program data management strategy must also ensure that numerical data are made available through standards and protocols that are readily compatible with these software tools. The Ocean Acidification Data Management Office should strive to support the broadest feasible range of desktop applications for statistical and numerical analysis and visualization and GIS (geographic information systems) tools for mapping and geospatial analysis. The Ocean Acidification Data Management Office should consult closely with its user communities to determine the specific software tools that must be supported.

Data Web Portal

As discussed in Theme 6, the FOARAM Act calls for the creation and maintenance of a Web portal for purposes of disseminating ocean acidification data and information. The education and outreach web portal will be separate, but complementary to, those that for data access; however their development and maintenance will be linked under the overall National Ocean Acidification Program. The data access framework that is adopted by the Ocean Acidification Data Management Office must be exposed through this portal. The website will serve as a clearinghouse at which users of ocean acidification data and scientists directly involved in the research efforts can locate, subset, download, and visualize relevant data and browse associated documentation and metadata.

Timely Availability of Data

Meeting the management and research goals of the National Ocean Acidification Program will require open and timely access to data and information from both Federal agencies and non-federal partners. Cultural barriers often inhibit the timely and complete release of data and metadata more than technical data networking considerations (Riebesell *et al.* 2010). The National Ocean Acidification Program should strive continually towards a goal of releasing all data as rapidly as feasible and should work with its partners to remove data access barriers and minimize delays in making data available to users.

Version Control and Citations to Data

In order to assure the quality of ocean acidification observations and assess problems with the ocean sensors that have been deployed, the ocean acidification monitoring program will include overlapping observations, such as ship tracks that periodically pass close to *in situ* mooring locations. The insights obtained through the analysis of differences between these observations will lead to re-processing of the raw observations – making adjustments for problems, such as drift in sensor calibrations where possible, and assigning quality control flags to the resultant observations. This is but one illustration of the need for the data management system to track observations at multiple levels of processing. Reproducible access to the precise version of data cited in publications is vital both to the integrity of the scientific process and for understanding the appropriate usage of products derived from the data (Hankin *et al.* 2010). *The Guide to Best Practices in Ocean Acidification Research and Data Reporting* (Riebesell *et al.* 2010) provides useful guidance on the use of Digital Object Identifiers (DOIs). The Ocean Acidification Data

Management Office must apply due diligence to ensure that citations to data are reproducible, while recognizing this as an area of emerging technology with solutions that must evolve over time.

Sensor Information Management

The National Ocean Acidification Program calls for an aggressive program of research and development intended to advance the design of chemical and biological sensors. Implicit in this plan will be a parallel evolution in the protocols that must be followed in order to deploy and utilize the sensors effectively. The National Ocean Acidification Program data management strategy must therefore ensure that accurate and detailed information about the sensors, measurement protocols, and processing are reliably captured and made available with the data. It must retain and catalog this information together with the relevant measurements, so that future users of ocean acidification observations can assess the sources of uncertainty in the data. The global ocean carbon flux community has provided a successful model of managing both the observations and information about the observation procedures, utilizing a blend of computer technology (e.g., the Mercury system, http://mercury.ornl.gov/) and adherence to associated community protocols. This model should be evaluated and, where appropriate, adopted in the strategy for ocean acidification data management.

Metadata

Many of the data management goals articulated above rely upon proper handling of metadata (information about where, when, and how data were generated, and by whom). A vital responsibility of the Ocean Acidification Data Management Program will be to ensure that, to the degree feasible, metadata needs are addressed "before field programs begin" (Glover *et al.* 2006, NRC 2010a). Glover *et al.* (2006) indicated that metadata must go beyond "conventions for standard methods, names, and units, as well as an agreed-to list of metadata to be collected along with the data," to include detailed descriptions of sensors, platforms, and their histories. This knowledge lies with the scientists, engineers, and technicians who create, install, and manage sensors, perform analyses, and run models. Thus, the science plans for the ocean acidification observations, modeling, and synthesis programs have a key responsibility in data management; they must define and enforce the protocols needed to ensure that metadata are captured reliably and effectively. Metadata records generated by the National Ocean Acidification Program should be made available through appropriate standards to be discoverable by national and international data integration frameworks such as GEOSS and Geodata.gov.

Archival

Ensuring the long-term preservation of the data assembled under the National Ocean Acidification Program will be a responsibility of the Ocean Acidification Data Management Office. The NRC report (2010a) suggests a sensible strategy: "The Program should identify appropriate data center(s) for archiving of ocean acidification data or, if existing data centers are inadequate, the Program should create its own."

A number of agencies have been exploring archival services for model outputs, but to date there is no established and funded program of this sort to handle ocean model outputs. Furthermore, instituting the archival of a new model output data stream will typically incur non-trivial

costs, the data volumes are usually considerable and increase over time, and the process of implementing responsible archival procedures involves careful creation and maintenance of metadata that captures the configuration of the model code and the specification of initial and boundary conditions. Standards and procedures to capture ocean acidification-related metadata do not yet exist, so this presents an additional development cost; however, rapid strides are being made in the development of metadata standards through model output management efforts such as the WCRP's Coupled Model Intercomparison Project, Phase 5 (CMIP5), which operates out of the Program for Climate Model Diagnosis and Intercomparison (PCMDI, http://www-pcmdi.llnl.gov/).

Support for Data Synthesis and Modeling

In Theme 2 of this strategic plan, we discuss the importance of data synthesis as a component of ocean acidification research. Effective data management is required to support such an activity in a collaborative, multi-agency context. A successful model of such a system is found in the international Surface Ocean Carbon Atlas (SOCAT, http://www.socat.info/) project, a synthesis activity under the auspices of the International Ocean Carbon Coordination Project (IOCCP, http://ioc3.unesco.org/ioccp/Index.html). The Ocean Acidification Data Management Office should strive to create a community "electronic commons" analogous to what SOCAT has provided. The electronic commons should be an environment in which scientists can evaluate data quality across the entire ocean acidification data collection, annotate the data with relevant insights, generate interpolated fields, and investigate outliers from these interpolated fields. As experience in the WCRP Coupled Model Intercomparison Projects (e.g., WCRP/CMIP3) has demonstrated, ocean acidification model intercomparison projects will also succeed at a much higher level if due consideration is given to data management support, including capturing and serving detailed model metadata (Williams *et al.* 2009).

Goals

A significant effort will be required to integrate very different types of ocean acidification data sets (physical, chemical, biological, and geological) from several agencies. A dedicated data management team will be required to perform this data integration. Some of the data management goals listed below are receiving some attention, but a coordinated ocean acidification data management effort has not yet been initiated. The short-term goals address issues that could be resolved quickly with adequate funding. The long-term goals should also be addressed as soon as possible, but they may take longer to yield their full benefits and/or require completion of one or more short-term goals.

***Short-term (3-5 years*)**

- Establish an Ocean Acidification Data Management Program (or Office). Under the guidance of this program:
    - Develop an initial data access web portal (complementary to education and outreach portal described in Theme 6).
    - Negotiate and implement system-specific approaches to interagency interoperability.
    - Develop a catalog of relevant data and documentation.
    - To the degree feasible make data and metadata accessible through uniform standards and protocols.

- Establish tools and procedures to support community-wide data synthesis, including careful control over versions of data.
- Establish initial collaborative relationships (domestic and international) and procedures to ensure archival of the data.
- Establish timeliness and data quality policies in conjunction with the science community.
- Harmonize with the emerging IOOS framework.

Long-term (10 year)

- Determine the components of the ocean acidification data access framework.
- Develop true system-of-systems integrated data and metadata exchange.
- Automate collection of metadata from "smart" sensors where feasible.

Budget

Several agencies have data management programs that could support the goals of this theme. The National Ocean Acidification Program office should work with these programs to identify available resources within the President's FY 2012 Request. Within the President's FY 2012 Budget, $152,000 has been identified for this purpose (NOAA and USGS).

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Appendix 1. Agency Programs Involved in Ocean Acidification Research

Department of the Interior (DOI)

The U.S. Department of the Interior's (DOI) marine and coastal responsibilities include 84 marine and coastal National Parks and 180 National Wildlife Refuges, numerous threatened and endangered species that depend on the ocean for survival, and some marine mammals including the polar bear, walrus, manatee, and sea otter. DOI also shares a concern for preserving these ecosystems and managing natural resources within these and other areas. The Department also manages offshore energy production and must take into consideration the environmental effects of these activities in relation to other environmental stresses. Ocean acidification will alter the environment and may have serious implications for the important areas managed by DOI, particularly since these areas include diverse ecosystems, such as coral and estuarine communities, and sediment resources. An understanding of the implications of ocean acidification is necessary to better manage these areas and to provide for adaptation to the altered environment. DOI, therefore, needs to be actively participating in identifying research needs as well as ensuring that appropriate scientific information is gathered to inform decision making.

- **National Park Service (NPS), Department of the Interior**
  The National Park Service is entrusted with managing 84 ocean and Great Lakes parks across 26 states and territories. These parks conserve over 12,500 miles of coast and 2.4 million acres of ocean and Great Lakes waters. NPS has adopted strategies to enhance the agency's organizational and scientific capacity to understand and conserve ocean and coastal park resources with state and Federal agencies and local organizations. The NPS conducts assessments of submerged maritime historic and cultural resources, and assessments of coastal watersheds and water resource conditions. The NPS also conducts long-term monitoring of marine ecosystems within its jurisdiction and maintains inventories of natural resources. The NPS Inventory and Monitoring Program provides a set of 12 baseline natural resource inventories on National Parks, which include presence, class, distribution, and status of biological resources such as plants and animals, and abiotic resources such as air, water, soils, and climate in certain coastal and estuarine locations.

- **United States Geological Survey (USGS), Department of the Interior**
  The USGS mission, as a bureau of DOI, is to provide sound scientific knowledge and information needed to understand environmental quality and resource preservation on regional, national, and, when appropriate, global scales. A number of programs within the USGS address such needs, including the Coastal and Marine Geology Program, Earth Surface Dynamics and Climate Change Research and Development, and various USGS Biology and Water Programs. Within the marine realm, the Coastal and Marine Geology Program and Climate Change coordinators recognize a need for research linking climate change and ocean acidification to marine ecosystem responses because of the significant resource management implications. Within the terrestrial aquatic realm, changes in river and lake chemistries have been characterized and monitored by USGS for decades. USGS research will continue to provide fundamental information on carbon and CO_2 cycling in these important areas and these data will aid the development of models that

describe ecosystem responses to chemical changes in the ocean and aquatic environments.

- **United States Fish and Wildlife Service (FWS), Department of Interior**
  The FWS has responsibility for many natural resources that could be affected by ocean acidification. The FWS Migratory Bird Program conserves migratory seabird populations and their habitats through careful monitoring, effective management, and by supporting national and international partnerships. The Service also has legal responsibility for many marine species listed under the Endangered Species Act and Marine Mammal Protection Act. The Service is concerned with how ocean acidification will affect the marine food webs that support these trust species. The Service also manages the National Wildlife Refuge System, which includes 106 marine protected areas, and shares management responsibility for four large Marine National Monuments in the Pacific Ocean. The Refuge System protects the most remote pristine coral reef ecosystems under U.S. jurisdiction. These coral reef refuges serve as natural laboratories for studying the effects of climate change and ocean acidification in the absence of other major human disturbances.

- Other DOI agencies with missions related to ocean acidification include the **Bureau of Ocean Energy Management, Regulation, and Enforcement (BOEM)** and the **Bureau of Land Management (BLM)**.

Department of State (DOS)

The U.S. Department of State (DOS) recognizes the importance of ocean acidification and its role in addressing this issue on an international scale with the cooperation of international partners. Although it does not currently manage any dedicated programs or funds for ocean acidification, DOS, along with the **U.S. Agency for International Development (USAID)**, is already progressing the understanding and acknowledgement of this issue. For example, DOS has raised ocean acidification in relevant international fora to advance public diplomacy, such as the Pacific Regional Environmental Programme, and has provided funding to various international ocean acidification activities, including the international workshop "Economics of Ocean Acidification." Involvement by DOS in this issue will likely increase and become more proactive, especially in the Bureau of Oceans and International Environmental and Scientific Affairs.

Environmental Protection Agency (EPA)

Under the Clean Air Act, EPA has developed regulations for the transportation and industrial sectors to reduce emissions of carbon dioxide and other greenhouse gases that contribute to ocean acidification, and EPA implements the Greenhouse Gas Reporting Program which will provide data to inform future Agency policies related to climate change. EPA is also responsible for protecting aquatic resources under the Clean Water Act, which charges EPA, States, Tribes and Territories to maintain and restore the chemical, physical, and biological integrity of the Nation's waters. The Act sets out several national goals, including the protection and propagation of fish, shellfish, and wildlife and recreation in and on the water through

enforcement of physical, chemical, and biological water quality standards. EPA supports actions to improve standards and reporting for marine and estuarine pH and is developing biological water quality standards for coral reefs and other aquatic resources, which can be used to protect against the consequences of ocean acidification.

National Aeronautics and Space Administration (NASA)

NASA's Earth Science Research Program supports research activities that address the Earth system to characterize its properties, to understand the naturally occurring and human-induced processes that drive them, and to improve our capability for predicting its future evolution. The focus of the Earth Science Research Program is the use of space-based measurements to provide information not available by other means.

The goals of the NASA Earth Science Research Program for Carbon Cycle Science are to improve understanding of the global carbon cycle and to quantify changes in atmospheric CO_2 and methane concentrations as well as terrestrial and aquatic carbon storage in response to fossil fuel combustion, land use and land cover change, and other human activities and natural events. NASA carbon cycle research encompasses multiple temporal and spatial scales and addresses atmospheric, terrestrial, and aquatic carbon reservoirs, their coupling within the global carbon cycle, and interactions with climate and other aspects of the Earth system.

Past projects have supported observation, research, modeling, satellite instrument requirement development, and education and public outreach investments in ocean acidification. In the most recent Carbon Cycle Science program element, NASA encouraged proposals for studies that address our understanding of ocean acidification and the impacts and feedbacks on ocean chemistry, ecology, and biology. These included but were not limited to (1) the impact of increasing or high CO_2 concentrations on ocean chemistry, (2) the evolving ability of the oceans to take up CO_2, and (3) the characterization and delineation of possible interactions between the effects of increasing pCO_2 and effects due to climate-induced changes in variables such as temperature and nutrients. To the extent possible, predictions of changes and quantification and characterization of impacts and feedbacks of ocean acidification on the broad ocean system, especially carbon dynamics, with the associated errors, were encouraged. Development of educational materials and outreach strategies related to ocean acidification and associated policies were also encouraged.

National Oceanic and Atmospheric Administration (NOAA), Department of Commerce

NOAA's mission is to understand and predict changes in Earth's environment and to conserve and manage coastal and marine resources to meet our Nation's economic, social, and environmental needs. In keeping with this mission and the requirements of the FOARAM Act, NOAA is (1) developing and deploying enhanced ocean and coastal observing systems, (2) conducting research and developing outreach plans to ensure protection of NOAA managed resources including fishery species and place based protected areas, (3) developing models to forecast future ocean chemistry and impacts on fishery species, and (4) educating the general public. As required by the FOARAM Act, NOAA has established a NOAA Ocean Acidification Program Office. The office is responsible for coordination of ocean acidification activities across

NOAA and will serve a coordinating role for NOAA Ocean Acidification activities as related to other Federal agencies, international inquiries, the media, Congress, non-governmental organizations, and the general public.

Scientists from NOAA's Office of Oceanic and Atmospheric Research work collaboratively with academic partners to conduct ocean carbon cycle research from ships, moorings, and floats in all major ocean basins. Current programs focus on open ocean physical and biogeochemical observations in support of long-term monitoring and prediction of the ocean environment on time scales from hours to decades. Studies are conducted to improve understanding of the complex physical and biogeochemical processes operating in the world oceans, to define the forcing functions and processes driving ocean circulation and the ocean carbon system, and to improve environmental forecasting capabilities and other supporting services for marine commerce and fisheries. Included are studies to assess the ocean's role in controlling atmospheric CO_2 levels with focus on observations of the exchange of CO_2 across the air-sea interface and its eventual penetration into the water masses of the deep ocean. Scientists within these laboratories are collaborating closely with NOAA Fisheries surveys and experimental research to assist in the analysis of carbon data samples and to expand the sampling effort related to carbon chemistry of the ocean, as it relates to managed and protected species. NOAA also plans to fund new sensor development related to detection and monitoring of ocean acidification through the Office of Oceanic and Atmospheric Research.

NOAA Fisheries Service studies are focused on assessing the physiological effects on individual living marine resources and the resulting ecosystem impacts. Through laboratory, field, and modeling studies, potential impacts are being examined on commercially and recreationally important fish and shellfish species and other species that are important components of marine ecosystems, including protected species. As noted above, collaborations with other parts of NOAA to monitor ocean acidification are ongoing.

Within the National Ocean Service, NOAA plans to administer a research program focused on the study of the impacts of ocean acidification on ocean and coastal ecosystems, including the development of ecosystem models to forecast future ecological and socioeconomic impacts. In addition, a research effort to develop an ecosystem monitoring network for coral reefs is continuing. Regionally specific ocean acidification research and outreach plans to manage and protect marine sanctuaries are being developed as are plans to add new ocean acidification-related parameters to long-term estuarine water quality monitoring at National Estuarine Research Reserves. Ocean acidification related data are also being collected and served by the Integrated Ocean Observing System via its regional associations.

NOAA's Satellite and Information Service recently developed an experimental product which translates satellite information and related modeled products into analysis and prediction of the impact of ocean acidification on coral reef regions.

National Science Foundation (NSF)

The NSF supports a broad spectrum of ocean acidification related research and educational activities that spans multiple disciplines, as well as capacity building within the scientific community.

Within the NSF's Directorate for Geosciences/Division of Ocean Sciences, Chemical and Biological Oceanography program managers have utilized funds from their core programs in the past few years to initiate ocean acidification research and technology development. The Biological Oceanography Program supports investigations of the impacts of ocean acidification on the biology, ecology, and biogeochemistry of planktonic and benthic systems of both the open ocean and coastal region, while the Chemical Oceanography Program has a strong emphasis on the impacts of ocean acidification on organic and inorganic geochemical materials in the oceans. Similar interests and investments exist in the NSF Office of Polar Programs.

Other NSF programs have also made investments in ocean acidification research. The Marine Geology and Geophysics program considers the genesis, chemistry, and mineralogical evolution of marine sediments, as well as interactions of continental and marine geologic processes andpaleoceanography; and the Geobiology and Low-Temperature Geochemistry program promotes studies of the interactions between biological and geological systems at all space and time scales. NSF's Program on Dynamics of Coupled Natural and Human Systems contributes to advance the ability to understand and predict the socioeconomic impacts of ocean acidification. Finally, NSF's Long-Term Ecological Research Program (LTER) supports the type of long-term interdisciplinary research necessary to understand the consequences of ocean acidification at the ecosystem scale.

The Directorate for Geosciences, the Directorate for Biological Sciences, and the Office of Polar Programs at the NSF together manage a limited-duration, focused program on ocean acidification to support research on three main research areas: (1) the chemistry and physical chemistry of ocean acidification and, in particular, its interplay with fundamental biochemical and physiological processes of organisms; (2) how ocean acidification interacts with processes at the organismal level, and how such interactions impact the structure and function of ecosystems; and (3) how the earth system history informs our understanding of the effects of ocean acidification on the present day and future ocean. The program has already awarded 22 grants (FY10-11) with a total investment of approximately $24 million for this focused program.

United States Navy

The U.S. Navy concerns surrounding ocean acidification stem from its relationship to climate change and national security. The Navy's Task Force Climate Change, which is directed by the Oceanographer of the Navy, was created to address the implications of climate change for national security and naval operations to ensure that the Navy is ready and capable to meet all mission requirements in the 21st century. Ocean acidification has the potential to increase instability in regions of the world where the effects of decreasing pH on marine life will threaten the food supply of over one billion people. The Navy is currently monitoring ongoing research to assess the implications of ocean acidification on future missions.

Appendix 2. Estimated Agency Budget Requirements by Theme

The budget estimates below represent funds, **in thousands of dollars**, provided in the President's FY 2012 Request to implement Themes 1-7 of the Strategic Research Plan.

	EPA	NASA	NOAA#	NSF	USGS	Total - All Agencies^
FY12 President's Budget Request (Total - All Themes)*	**$0**	**$2,025**	**$11,600**	**$15,500**	**$1,755**	**$30,880**
Theme 1: Monitoring of Ocean Chemical and Biological Impacts	$0	$375	$5,575	$2,500	$1,201	**$9,651**
Theme 2: Research to Understand Responses to Ocean Acidification	$0	$1,125	$2,949	$10,000	$354	**$14,428**
Theme 3: Modeling to Predict Changes in the Ocean Carbon Cycle and Impacts on Marine Ecosystems and Organisms	$0	$375	$1,090	$1,500	$100	**$3,065**
Theme 4: Technology Development and Standardization of Measurements	$0	$0	$1,487	$1,000	$25	**$2,512**
Theme 5: Assessment of Socioeconomic Impacts and Development of Strategies to Conserve Marine Organisms and Ecosystems	$0	$0	$297	$0	$0	**$297**
Theme 6: Education, Outreach, and Engagement Strategy on Ocean Acidification	$0	$150	$100	$500	$25	**$775**
Theme 7: Data Management and Integration	$0	$0	$102	$0	$50	**$152**

* Agency totals are based upon the President's FY 2012 Request. Allocation among the themes is estimated.

Costs for the NOAA OA Program Office, including 3 full-time employees, will come out of this budget, assuming no other funds are designated for this purpose.

^ Other Federal agencies not included here may have indirect activities that could be enhanced or modified to address ocean acidification.

Appendix 3. Acronyms and Abbreviations

AAAS	American Association for the Advancement of Science
ACT	Alliance for Coastal Technologies
AGU	American Geophysical Union
AOAT	Atlantic Ocean Acidification Test-Bed
ASLO	American Society of Limnology and Oceanography
ARMS	Autonomous Reef Monitoring Structures
ASTC	Association of Science - Technology Centers
AUVs	Autonomous underwater vehicles
BATS	Bermuda Atlantic Time-series
BCO-DMO	Biological and Chemical Oceanography Data Management Office
BOEM	Bureau of Ocean Energy Management, Regulation, and Enforcement
BOGCM	Biogeochemistry ocean general circulation model
$CaCO_3$	Calcium carbonate
CCEP	Climate Change Education Partnership
CLEAN	Climate Literacy and Energy Awareness Network
CLIVAR	Climate Variability and Predictability
CMIP5	Coupled Model Intercomparison Project, Phase 5
CO_2	Carbon dioxide
CO_3	Carbonate
CoML	Census of Marine Life
COSEE	Centers for Ocean Sciences Education Excellence
CRCP	Coral Reef Conservation Program
CRED	Coral Reef Ecosystem Division (NOAA Pacific Islands Fisheries Science Center)
CRMs	Certified Reference Materials
DIC	Dissolved inorganic carbon
DMAC	Data Management and Communications
DOC	Dissolved organic carbon
DOE	Department of Energy
DOM	Dissolved organic matter
DOS	Department of State
EPA	Environmental Protection Agency
EPOCA	European Project on Ocean Acidification
FOARAM Act	Federal Ocean Acidification Research and Monitoring Act of 2009
FOCE	Free-ocean carbon dioxide experiment
GEO-IDE	Global Earth Observation-Integrated Data Environment
GEOSS	Global Earth Observation System of Systems
GIS	Geographic Information Systems

GO-SHIP	Global Ocean Ship-based Hydrographic Investigations Program
GDP	Gross Domestic Product
HOT	Hawaii Ocean Time-series
IAM	Integrated Assessment Models
IBMs	Individual-based models
IMBER	Integrated Marine Biogeochemistry and Ecosystem Research
IOOS	Integrated Ocean Observing System
IPCC	Intergovernmental Panel on Climate Change
IWG-OA	Interagency Working Group on Ocean Acidification
I&M	Inventory and Monitoring
JPL	Jet Propulsion Laboratory
LCC	Landscape Conservation Cooperatives
LTER	Long-term Ecological Research (Network)
LULUC	Land-use-land-use-change (model)
MBARI	Monterey Bay Aquarium Research Institute
NASA	National Aeronautics and Space Administration
NEP	National Estuary Program
NERRS	National Estuarine Research Reserve System
NGO	Non-governmental organization
NOAA	National Oceanic and Atmospheric Administration
NOC	National Ocean Council
NRC	National Research Council
NPS	National Park Service
NRInfo	Natural Resource Information Portal
NSF	National Science Foundation
NWRS	National Wildlife Refuge System
OA-ISMAs	Ocean acidification intensively studied marine areas
OATF	Ocean Acidification Task Force
OCB	Ocean Carbon and Biogeochemistry (Program)
OOI	Ocean Observatories Initiative
OOI-CI	Ocean Observatories Initiative CyberInfrastructure
ORRAP	Ocean Research and Resources Advisory Panel
OPTF	Ocean Policy Task Force
OSSEs	Observing System Simulation Experiments
OTIC	Oceanographic Technology and Interdisciplinary Coordination
pCO_2	Partial pressure of carbon dioxide
PCMDI	Program for Climate Model Diagnosis and Intercomparison
PICCC	Pacific Islands Climate Change Cooperative
PIC	Particulate inorganic carbon
PIFSC	Pacific Islands Fisheries Science Center

POC	Particulate organic carbon
QA/QC	Quality assurance/quality control
ROMS	Regional Ocean Modeling Systems
SeaBASS	SeaWiFS (Sea-viewing Wide Field-of-view Sensor) Bio-optical Archive and Storage System
SBIR	Small Business Innovation Research
SHARQ	Submersible Habitat for Analyzing Reef Quality
SOCAT	Surface Ocean Carbon Atlas
SOLAS	Surface Ocean Lower Atmosphere Study
SOPs	Standard Operating Procedures
SOST	Subcommittee on Ocean Science and Technology
TA	Total alkalinity
FWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
USGCRP	U.S. Global Change Research Program
VOS	Voluntary Observing Ships
WOCE	World Ocean Circulation Experiment
WCRP	World Climate Research Program