Ocean Acidification
– Recommended Strategy for a U.S. National Research Program –

Ocean Carbon and Biogeochemistry Program
Subcommittee on Ocean Acidification

March 25, 2009

- **The increase in carbon dioxide concentration in the atmosphere is forcing more carbon into our oceans, causing changes in seawater chemistry known as "ocean acidification."**
- **Ocean acidification is distinct from climate change, and presents a separate suite of environmental changes that will affect ocean ecosystems, fisheries, and other marine resources in profound ways, such as reducing the ability of many organisms to build their shells, and changing organisms and ecosystems in ways that affect the carbon and nitrogen cycles.**
- **The seriousness of this issue has only recently recognized, but the scale of potential impacts has led to consistent appeals from the scientific community, both nationally and internationally, to escalate ocean acidification research.**
- **The urgency and global nature of ocean acidification call for the establishment of a U.S. National Research Program that draws from the expertise of multiple agencies within a coordinated plan.**

1. Introduction

Definition. Ocean acidification refers to the decrease in the pH of the Earth's oceans caused by the uptake of carbon dioxide from the atmosphere. This consequence of fossil fuel burning is an urgent issue because of the potential global-scale impacts it presents across a broad spectrum of marine life.

Distinction from climate change. Ocean acidification is related to, but distinct from, climate change. Both climate change and ocean acidification share a common cause: increasing carbon dioxide concentration in the atmosphere. Rising levels of carbon dioxide (CO_2) gas, along with other greenhouse gases, indirectly alter the climate system by trapping heat that perturbs the Earth's radiation budget. Ocean acidification is not a climate process, but instead directly impacts ocean chemistry as seawater absorbs carbon dioxide from the atmosphere. Unlike the uncertainties inherent in climate change models, predictions of ocean acidification are very robust. The distinction between climate change and ocean acidification is important because discussions regarding both solutions and adaptation to climate change often ignore ocean acidification. Some geo-engineering solutions, for example, might lessen the impacts of the global warming but do nothing to reduce ocean acidification.

This white paper argues for the establishment of a **U.S. National Research Program on Ocean Acidification** and outlines the necessary components of such a Program. The U.S. Ocean Carbon and Biogeochemistry Program, who's mission is *to establish the evolving role of the ocean in the global carbon cycle, in the face of environmental change, through studies of marine biogeochemical cycles and associated ecosystems,* has established that the needs for such a National Research Program are as compelling and urgent as those addressed by national-level climate change programs. Because we presently understand little about how ocean acidification will affect marine ecosystems, services and resources, and therefore our economy, an ocean acidification program must include a level of coordination and funding that will accelerate discovery to a pace that can adequately inform decision-making.

The Ocean Research Priorities Plan (ORPP) and Implementation Strategy[1] lists 20 national ocean research priorities for the coming decade, and ocean acidification is an issue that cuts across many of these. Ocean acidification research is already becoming a research priority within several government agencies, and planning is needed to coordinate and manage activities between agencies.

2. Why ocean acidification is an issue

The process. Carbon occurs naturally and in abundance in seawater, simultaneously as a suite of multiple compounds or ions, including dissolved carbon dioxide ($CO_{2(aq)}$), carbonic acid (H_2CO_3), bicarbonate ions (HCO_3^-), and carbonate ions (CO_3^{2-}). This is called the "CO_2 system in seawater." The relative proportion of these compounds and ions adjusts to maintain the ionic charge balance in the ocean – something that is termed the "carbonate equilibrium" of seawater or the "carbonate buffering system." Addition of CO_2 to seawater alters the carbonate equilibrium, with an associated decline in pH and changes in the relative concentrations of bicarbonate and carbonate ions.

The impacts. Ocean acidification is linked to a multitude of direct and indirect impacts on marine life that are occurring in concert with other impacts such as climate change, but some important biological effects are now clearly evident. For instance, ocean acidification will reduce calcification rates in corals and may affect economically important shellfish species including oysters, scallops, mussels, clams, sea urchins, crabs and lobsters. Some organisms may benefit from ocean acidification, while others will be negatively impacted, and the impacts may differ from one life stage to another (i.e., adults, eggs, larvae, juveniles, etc.). Overall, the net effect is likely to disrupt the normal functioning of many marine and coastal ecosystems. However, we are currently unable to predict the net impacts on most marine ecosystems or the services they provide such as fisheries and coastline protection.

[1] NSTC Joint Subcommittee on Ocean Science and Technology (2007) Charting the Course for Ocean Science in the United States for the Next Decade, An Ocean Research Priorities Plan and Implementation Strategy, January 26, 2007, 84 pp.

2.1 Direct effects

Marine biological processes can be directly impacted by ocean acidification because of changes in pH, or changes in the concentrations of dissolved carbon dioxide, bicarbonate ion, or carbonate ion. Virtually every major biological function has been shown to respond to these chemical changes in seawater, including photosynthesis, respiration rate, growth rates, calcification rates, reproduction, and recruitment.

pH. Since the biochemical processes of virtually all living organisms are regulated by pH, most organisms expend energy to regulate their cellular and internal pH. Some organisms are better equipped to handle changes in pH than are others. Since pH is a measure of the hydrogen ion concentration, reported on a logarithmic scale, small changes in pH indicate large changes in hydrogen ion concentration. For example, the average pH of the surface ocean has decreased by nearly 0.1 unit since preindustrial times, which is equivalent to a 30% increase in the hydrogen ion concentration (or "acidity"[2]) of the ocean.

$CO_{2(aq)}$ and HCO_3^-. Concentrations of both dissolved carbon dioxide and bicarbonate increase with ocean acidification. The marine primary producers – the base of marine food webs – use both forms of carbon. Sea grasses are marine plants that, like terrestrial plants, use $CO_{2(aq)}$ for photosynthesis and are likely to benefit from its increased availability with ocean acidification. Some microscopic phytoplankton also seem to benefit from increases in $CO_{2(aq)}$ or HCO_3^-. However, changes in the concentrations of carbon dioxide and bicarbonate may have implications for the *types* of algae that dominate, thus changing the nature of marine food webs.

CO_3^{2-}. Changes in the carbonate ion concentration affect the "saturation state" of the various calcium carbonate minerals that are used by marine organisms to produce their shells or skeletons. The carbonate ion concentration decreases dramatically with ocean acidification – by 30% once atmospheric carbon dioxide concentration is twice the preindustrial level. This decreased availability of carbonate ions will limit shell and skeletal formation of many organisms, including corals, shellfish, sea urchins, and many algae. These changes are some of the better documented and alarming impacts of ocean acidification. For example, well-controlled laboratory experiments have shown that the projected reduction in CO_3^{2-} will reduce growth of adult corals and slow the development of newly settled corals. This century, coral reefs may cross the threshold where reef building does not keep up with natural and human caused reef destruction, and where recruitment of new corals is out-paced by coral death.

2.2 Indirect effects

Ocean acidification can also affect marine organisms indirectly, whether or not they are directly affected by changes in carbonate chemistry. Here are some of the ways:

---

[2] Technically, the oceans are alkaline and will not become acidic in the near future. The term refers to the process of increasing hydrogen ion concentration, and the shift of ocean pH toward more acidic conditions.

Chemical speciation of nutrients and metals. Changes in pH, a fundamental chemical property of seawater, can alter the availability of nutrients, trace elements and trace organics that support marine life. The chemical form of several trace metals, for example, can be altered by changes in pH, making them more or less available (or more or less toxic) to marine organisms.

Biogeochemical processes. The major nutrient cycles in the ocean, which include geological, chemical, physical, and biological processes, determine the availability of nutrients that support all ocean life, as well as the ability of the oceans to sequester CO_2 from the atmosphere. Ocean acidification has the potential to alter both chemical and biological processes that will affect nutrient and carbon cycles, such as by altering the rate of nitrogen fixation by certain marine algae.

Food web effects. Because marine food webs can be complex, changes in one or more key species can have repercussions throughout the food web. This is one of the main concerns regarding U.S. fisheries, but predicting such changes may also be one of the greatest research challenges within ocean acidification research. Even those species that are not directly impacted by ocean acidification can be indirectly affected by changes in their food supply, competitors, or predators.

Changes in ecosystem substrate. In some communities, particularly bottom dwellers, decreases in calcium carbonate production alter the structural fabric of the ecosystem. Many marine plants and animals depend on the structural habitat provided by coral reefs and cold-water coral communities. Oyster banks, clam beds, etc. may also be affected by substrate changes associated with decreased carbonate production.

3. Research Strategy

3.1 Building on existing workshops/reports and research

Several workshop reports and reviews of existing ocean acidification research at the national and international levels (see bibliography) unanimously emphasize the serious nature of ocean acidification threats, and call for large-scale programs that address the many elements of ocean acidification within a coordinated research effort.

Ocean acidification has emerged as a top priority within various U.S. and international organizations and programs not only within the U.S. Ocean Carbon and Biogeochemistry (OCB) Program, but also in the following:

- Integrated Marine Biogeochemistry and Ecosystem Research Project (IMBER)
- Scientific Committee on Oceanic Research (SCOR)
- UNESCO's Intergovernmental Oceanographic Commission (IOC)
- International Atomic Energy Agency (IAEA) Marine Environment Laboratories
- Surface Ocean Lower Atmosphere Study (SOLAS)
- International Geosphere-Biosphere Program (IGBP; *e.g.* the Past Global Changes (PAGES) Project)
- Consortium for Ocean Leadership (COL)

Several of our international colleagues have developed national and multi-national programs for ocean acidification research. The European Commission has funded the European Project on OCean Acidification (EPOCA), an initiative to investigate "Ocean acidification and its consequences" as a multinational effort that includes 29 laboratories located in nine European countries. EPOCA research, already underway, aims to monitor ocean acidification and its effects on marine organisms and ecosystems, to identify the risks of continued acidification, and to understand how these changes will affect the Earth system as a whole. One of EPOCA's priorities is to establish a strong E.U.-U.S. collaboration in ocean acidification research. In addition, two anticipated national programs within E.U. home countries will augment EPOCA research: in the U.K., a 5-year program to investigate changes in ocean ecosystems in response to ocean acidification (funded by the Natural Environment Research Council), and in Germany, a program entitled Biological Impacts of Ocean Acidification (BIOACID) (funded by BMBF (*Bundesministerium für Bildung und Forschung*), the Federal Ministry of Education and Research).

In the People's Republic of China, CHOICE-C is a newly funded 5-year multi-institution project to study high CO_2 and ocean acidification issues in Chinese marginal seas. This project involves research groups from various universities and federal government entities, with emphasis on: 1) constraining and quantifying air-sea CO_2 fluxes, 2) constructing an overall pelagic carbon budget, and 3) determining the potential ecological and economic impacts of ocean acidification, including the use of manipulative experiments. Chinese investigators and funding agencies are interested in collaborating with U.S. scientists, and opportunities may exist for sharing research and ship time.

Five major programs in Japan fund research relevant to ocean acidification. Japan's Ministry of Environment ministry supports research programs to elucidate the future impact of ocean acidification on various marine organisms using sophisticated mesocosm facilities (*e.g.* AICAL, Acidification Impact on CALcifiers). MEXT (Ministry of Education, Science, Sport and Culture) and JAMSTEC (Japan Agency for Marine Science and TEChnology) also support ocean acidification research such as modeling efforts on the Earth Simulator supercomputer to predict future ocean conditions.

The Korea Science and Engineering Foundation is funding the 5-year Korea Mesocosm Project to examine the effects of surface CO_2 and temperature elevation on natural phytoplankton assemblages, which involves five Korean laboratories. The Korean government has also funded the project "Impact of climate change on marine ecosystems" (2008–2013) that includes laboratories across four Korean Institutes.

Ocean acidification in Australia focuses on Antarctic through Australasian regions. CSIRO research in the Southern Ocean includes monitoring seawater chemistry changes and the responses of key species. In the tropics, a collaborative observational and modeling program between CSIRO, NOAA, NIES (Japan) and University of Queensland has begun in the Great Barrier Reef and South Pacific regions. The vulnerability of the Great Barrier Reef to ocean acidification is also being addressed by the Australian Institute of Marine Science and several universities (Australian National Univ., Univ.

Queensland, Univ. Sydney, James Cook Univ.) through large-scale monitoring of reef waters, paleontological reconstructions from coral cores, and field and laboratory experiments on reef organisms.

Research programs are underway in New Zealand by marine science academic organizations and the National Institute for Water and Atmosphere (NIWA) to examine acidification impacts on ocean chemistry, algal calcification, and phytoplankton production and community function.

3.2 Recommended U.S. research strategy

The United States research community has lead major efforts to define the scope of research needed on ocean acidification. Moving forward to implement those research plans requires the establishment of a **U.S. National Program** that draws from the expertise of many federal agencies and academic institutions. The needs of such a program are clearly articulated and will be addressed by an upcoming National Research Council report.

3.3.1 Key recommendations from Scripps Report

In October 2007, the U.S. OCB Program, with funding from NOAA, NSF, and NASA sponsored a workshop on Ocean Acidification at the Scripps Institution of Oceanography to identify U.S. research needs over the next 5-10 years. This workshop assimilated input from some 100 scientists into a report[3] that laid out a strategy to address present and future ocean acidification impacts in four important marine environments: warm water coral reefs, coastal margins, tropical to subtropical open-ocean regions, and high-latitude regions (Arctic and Southern Oceans). The key recommendations for research include:

- Establish a national program on ocean acidification research;
- Develop new instrumentation for the autonomous measurement of CO_2 system parameters, particulate inorganic carbon (PIC), particulate organic carbon (POC), and physiological stress markers;
- Standardize protocols for manipulation and measurement of seawater chemistry in experiments and for calcification and other rate measurements;
- Expand existing ocean CO_2 system monitoring to include new monitoring sites/surveys in open-ocean and coastal regions, including sites considered particularly vulnerable to ocean acidification, and sites that can be leveraged for field studies;
- Establish new monitoring sites/surveys in open-ocean and coastal regions, including sites of particular interest such as the Bering Sea;
- Progressively build capacity and initiate planning for mesocosm and CO_2-perturbation experiments in the field;
- Build shared facilities to conduct well-controlled CO_2-manipulation experiments;

[3] Fabry et al., (2008a) Present and Future Impacts of Ocean Acidification on Marine Ecosystems and Biogeochemical Cycles. Report of the Ocean Carbon and Biogeochemistry Scoping Workshop on Ocean Acidification Research, 9–11 October 2007. Scripps Institution of Oceanography, University of California, San Diego, CA.

- Perform global data/model synthesis to predict and quantify alterations in the ocean CO_2 system due to changes in marine calcification;
- Develop regional biogeochemical models and conduct model/data intercomparison analyses;
- Establish international collaborations to create a global network of CO_2 system observations and field studies relevant to ocean acidification;
- Ensure that the research is designed to provide results that are useful for policy and decision-making; and
- Initiate specific activities for education, training, and outreach.

3.3.2 Needed Facilities

A major challenge to advancing the science of ocean acidification is the lack of suitable facilities for conducting experiments. Ocean acidification research poses considerable barriers to many if not most investigators because only a few laboratories are capable of high-quality carbonate chemistry measurements, and because there is no central laboratory available for conducting acidification experiments on marine organisms and communities.

Such facilities should include the ability to 1) conduct experiments from aquaria to open-ocean, 2) to study both short-term and long-term effects on a series of biological responses (e.g., photosynthesis, growth, reproduction, etc.), and 3) to examine the responses of the entire life cycles of organisms (e.g., for a fish or oyster species, this includes the effects on eggs, larvae/juveniles, as well as adults and their reproductive capacities). A typical facility might consist of a series of experimental tanks in which the seawater CO_2 system can be manipulated and monitored to simulate both past (low CO_2) and future (high CO_2) environments. Also needed are standardized, mobile carbonate chemistry labs that can be deployed on ships or to remote field stations. Finally, there is an immediate need for a select number of qualified laboratories where researchers can send samples for high precision carbonate chemistry measurements, and which offers training on sample collection and analysis.

3.3.3 Review by the National Research Council

The 2006 reauthorization of the Magnuson-Stevens Act called for NOAA to enter into an agreement with the National Academy of Sciences (NAS) to initiate a study on acidification and its impacts (see Public Law 110-161). This review: *Development of an Integrated Science Strategy for Ocean Acidification Monitoring, Research, and Impacts Assessment*, will be conducted by the Ocean Studies Board through the year 2009.

Building on the recommendations of this whitepaper (i.e., the creation of a U.S. National Research Program on ocean acidification), the NAS report will "recommend priorities for a national multi-agency research, monitoring, and assessment plan to advance understanding of the biogeochemistry of carbon dioxide uptake in the ocean and the relationship to atmospheric levels of carbon dioxide, and to reduce uncertainties in projections of increasing ocean acidification and the potential effects on living marine resources and ocean ecosystems." The Ocean Carbon and Biogeochemistry Program strongly supports this activity, and will cooperate fully with the NAS to provide any necessary scientific information and guidance.

3.3.4 Cost of a U.S. Research Program on Ocean Acidification

Our understanding of ocean acidification is in its infancy, and initial assessments suggest that the research required to understand its extent and risks will realistically require new resources beyond what can be carved out of existing agency budgets. Just documenting the extent of the problem and its ramifications through food webs will require significant resources involving ships, buoys and autonomous platforms, which by their nature are expensive.

The research strategies proposed during the OCB-sponsored workshop noted above acknowledged that resources are not infinite, and objectives must be carefully prioritized. This task has been difficult, as the list of oceanographic effects imposed by ocean acidification continues to grow, and scientific research plans have had to continually expand to address new discoveries.

We can roughly frame the costs, however, within the context of budgets for previous multi-agency ocean research programs. For example, the broad nature of an ocean acidification program will require both a biogeochemical emphasis (similar to the U.S. Joint Global Ocean Flux Survey) as well as the effects on high-order organisms and ecosystems (similar to the U.S. GLOBEC Program, GLOBal Ocean ECosystem Dynamics). The NSF (only) contributions to JGOFS and GLOBEC[4] totaled about $17–22 million per year. The additional contributions from NOAA, NASA, and DOE to these programs are estimated to have doubled the total funding to around $40–45 million per year.

In order to obtain timely information relevant to managers and decision-makers, a U.S. National Research Program on Ocean Acidification will realistically need on the order of $50 million per year. $30 million per year may be appropriate for the first 2–3 years, while large-scale efforts are still being planned, but once the program is fully engaged, $50–100 million per year is considered the *minimum* if scientists are to provide useful information regarding how the oceans are responding to acidification, and how we should change our mitigation and adaptation policies. On March 25, 2009, Congress passed the FOARAM Act (Federal Ocean Acidification Research and Monitoring Act) to address U.S. ocean acidification research, with authorizations on the order of $10–35 million per year[5]. These authorizations are modest compared to similarly sized programs described above, but will certainly provide badly needed resources toward building a U.S. National Research Program on Ocean Acidification.

---

[4] GLOBal Ocean ECosystem Dynamics http://www.usglobec.org/

[5] The FOARAM Act, passed in the House under H.R. 146 Omnibus Public Land Management Act of 2009 (Title XII, Subtitle D - Federal Ocean Acidification Research and Monitoring Act of 2009) authorizes appropriations for fiscal years 2009, 2010, 2011, and 2012, at $14 million, $20 million, and $27 million, and $35 million per year, respectively. See http://www.govtrack.us/congress/vote.xpd?vote=h2009-153 for details.

As daunting as this problem may seem, the societal cost of inaction are likely much greater. Our oceans provide tremendous resources, including a major source of revenue for the U.S. (the commercial fish harvest is about $4 billion per year), and a major source of nutrition for the world population (the FAO estimates that fish provide at least 20% of the total per capita animal protein intake[6]). Determining how a changing ocean pH will affect fishery resources and other valuable ocean services are in the best interest of society and national security. Yet the value of our oceans extends well beyond such economic assessment; ocean acidification presents considerable risk to overall functioning of marine ecosystems that keep the Earth system in balance. Understanding ocean acidification and its consequences is quite possibly the oceanographic challenge of the decade (possibly century), but is a challenge that oceanographers can meet provided there is a national commitment to fund the work.

3.3 Relevant U.S. Agencies within a National Ocean Acidification Program

In the United States, NOAA, NSF, and NASA have shifted, or plan to shift, a portion of their existing internal funds to sponsor certain aspects of ocean acidification research, but these funds are small relative to the research needs, and the justification for coordinating research across these various agencies is obvious. Within the U.S. Ocean Carbon and Biogeochemistry (OCB) program, which is jointly sponsored by NSF, NOAA and NASA, ocean acidification has been identified as a top research priority. Other agencies have also shown an interest in participating in a national program on ocean acidification research, such as the USGS, which already conducts ocean acidification research, and the EPA, which is the lead Federal agency responsible for protecting the Nation's water quality.

3.3.1 National Oceanic and Atmospheric Administration (NOAA)

NOAA has specific research and management responsibilities for U.S. marine ecosystems and living marine resources. These responsibilities require an understanding of the status of these ecosystems, including ecosystem changes due to climate change and ocean acidification that are likely to affect them. The NOAA ocean acidification research program is designed to have the following goals: 1) to develop a comprehensive characterization of the threat ocean acidification poses to marine ecosystems, 2) to develop the monitoring capacity to quantify and track ocean acidification and its impacts in oceanic and coastal systems, 3) to develop an improved ocean acidification forecasting capability to provide stakeholders with the capacity to proactively and appropriately respond to ocean acidification, and 4) to develop adaptive management tools and requisite scientific knowledge for understanding and responding to ocean acidification in support of ecosystem-based management. To carry out these goals, NOAA is continuing its present program of ocean carbon inventories and CO_2 flux studies. In addition to these activities, NOAA is also planning new research in technology development and remote sensing applications: CO_2 moorings, coral reef monitoring networks, environmental modeling, physiological response research, plus the development of mitigation and adaptation strategies for resource managers.

---

[6] FAO (2007) The State of World Fisheries and Aquaculture, FAO Fisheries and Aquaculture Department, United Nations, Rome, 2006, ISSN 1020-5489.

3.3.2 National Science Foundation (NSF)

The National Science Foundation supports a broad spectrum of ocean acidification related research and educational activities that spans multiple disciplines, particularly within the Division of Ocean Sciences (OCE). 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 regions, while the Chemical Oceanography Program has a strong emphasis on the impacts of ocean acidification on organic and inorganic geochemical materials in the oceans. The NSF Chemical and Biological Oceanography program managers have already diverted significant funds from their own programs to support ocean acidification research. Other NSF programs offer significant expertise in ocean acidification research. Marine Geology and Geophysics (MGG) considers the genesis, chemistry, and mineralogical evolution of marine sediments, as well as interactions of continental and marine geologic processes and paleoceanography; and Geobiology and Low-Temperature Geochemistry (GG) 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 could advance our ability to understand and predict the socio-economic 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.

3.3.3 National Aeronautical and Space Administration (NASA)

NASA's Ocean Biology and Biogeochemistry research program is focused on improving our understanding of the ocean ecosystems to climate change and ocean acidification through cutting-edge space-borne global observing capabilities, and integrating new knowledge of the Earth system into predictive models. NASA's ocean research programs encompass the sub-disciplines of Physical Oceanography and Ocean Biology & Biogeochemistry. The goals of these NASA ocean programs are to: 1) develop a predictive understanding of global ocean ecosystem health, productivity, biodiversity, and trophic dynamics; 2) determine the changes in biodiversity of ocean ecosystem over time; and 3) understand how elements cycle within the oceans and how much food and energy can be provided by ocean ecosystems, as well as accurately assess marine primary production and monitor indices of ecosystem health.

3.3.4 United States Geological Survey (USGS)

The USGS mission 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, and various USGS Biology Programs. Within the marine realm, the Coastal and Marine Geology Program coordinators recognize a need for research linking climate change and ocean acidification to marine ecosystem responses because of the significant resource management implications. Coastal and marine ecosystems, including coral reefs, bays and estuaries, and continental margins are particularly sensitive to climatic change and ocean acidification. Therefore, USGS research will continue to provide fundamental information on CO_2 cycling in these important areas and these data will aid the development of models that describe ecosystem responses to CO_2 changes in the ocean.

3.4 Interagency Coordination

The ORPP Implementation Strategy established a strong basis for carrying out ocean research priorities by including: 1) use of existing mechanisms to address ocean research priorities, 2) partnerships (local, tribal, state, federal, international, etc.), 3) peer-review, 4) balancing sustained effort with new initiatives, and 5) accounting for different scales of research efforts and needs. A new governance structure established under the Committee on Ocean Policy expands the capacity for coordinating efforts across various federal agencies. The Joint Subcomittee on Ocean Science and Technology (JSOST; National Science and Technology Council) in particular provides for the coordination of science and technology across multiple federal agencies.

Within the proposed FOARAM legislation, JSOST is designated as the Subcommittee that will coordinate Federal activities on ocean acidification. Under this plan, JSOST would establish an interagency working group to develop the strategic research and monitoring plan to guide Federal research on ocean acidification. This plan would include: 1) assessing of the potential impacts of ocean acidification on marine organisms and marine ecosystems; 2) developing adaptation and mitigation strategies to conserve marine organisms and ecosystems exposed to ocean acidification; 3) facilitating communication and outreach opportunities with nongovernmental organizations and members of the stakeholder community with interests in marine resources; 4) coordinating the United States Federal research and monitoring program with research and monitoring programs and scientists from other nations; and 5) establishing an Ocean Acidification Information Exchange 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.

Regardless of whether a National Program on Ocean Acidification Research is established through the FOARAM Act or by some other means, the OCB agrees that JSOST or some similar structure will be required to coordinate the wide range of scientific contributions from the various research agencies. Another model would be to establish a scientific steering committee that includes scientists and representatives from each of the participating agencies to oversee scientific direction, similar to the scientific steering committee of the U.S. Joint Global Ocean Flux Survey.

3.5 Outreach

Because ocean acidification will have consequences that impact our socio-economic systems, it is imperative to inform multiple sectors of society of what is known about ocean acidification and its potential impacts not only on marine ecosystems, but also on day-to-day living. However, ocean acidification is a difficult concept to convey to most of the American Public, particularly those who have had little contact with the ocean. A national ocean acidification program is thus obligated to provide information not only to researchers, but also to policy-makers, teachers, and the public, and thus will require skilled and dedicated effort operating alongside the research program. Emphasis should be placed on encouraging stakeholder support for and participation in marine ecosystem conservation. Examples of education and outreach activities include: workshops and training programs with constituents to provide internet access and orientation to current research findings and data; planned development and distribution of educational materials and displays; fostering local community involvement in conservation and restoration projects; and hosting two-way discussions with stakeholders to improve mutual understanding of resource needs and management goals. Several websites are available or are being developed to support these activities (e.g. the OCB Ocean Acidification website listed below).

4.0 A Phased Research Plan

Although the U.S. has been involved in ocean acidification research for a decade, that research has almost entirely been conducted by individual researchers. A **U.S. National Research Program** will streamline ocean acidification research by integrating research, monitoring, modeling and assessment along a common timeline.

Particular research needs that are not yet addressed by our international colleagues and that U.S. agencies are well-positioned to undertake include global monitoring of open ocean waters as well as monitoring of U.S. coastal and upwelling regions, field surveys to establish biological responses to ocean acidification, large-scale field experiments, and ecosystem-scale studies within the four major systems identified at the Scripps meeting: warm water coral reefs, coastal margins, tropical to subtropical open-ocean regions, and high-latitude regions (Arctic and Southern Oceans).

The two phases of activities below are based on the prioritization of research needs, the ability to leverage on existing facilities and knowledge, as well as practical considerations such as the lead-time needed for technological development and modeling.

Phase 1; 0-5 years

- Interagency plans for research and infrastructure facilities for monitoring systems, laboratory-based physiological response studies, and modeling capabilities are established.
- Standardized measurement protocols and data reporting guidelines are developed for ocean acidification field and laboratory measurements.
- Data management protocols (reporting, dissemination, and archival) for ocean acidification research activities are developed to ensure both rapid and long-term accessibility.
- Shared facilities are constructed to conduct well-controlled CO_2-manipulation experiments.
- Synthesis of global observations and model data are performed to determine baseline biogeochemical and ecological states (*e.g.* calcium carbonate cycle), and to predict and quantify future changes in these states due to ocean acidification.
- Field research and autonomous systems for measurement of additional parameters

of the seawater CO_2 system are developed and tested for seagoing platforms.

- Regional networks of observations and key processes are established. As new autonomous sensors become available, they are deployed on existing moored platforms, floats and gliders.
- Regional biogeochemical models are established to predict and quantify biological impacts.
- Species-specific physiological responses of commercially ecologically important species to ocean acidification are investigated, and forecasts of ecological and economic consequences of impacts are developed.
- Ecological monitoring studies in key habitats are established.

Phase II; 5-10 years

- An international, global network of ocean carbon system and pH observations and process studies is established. Autonomous sensors on moored buoys, floats and gliders are used extensively.
- Applications using data from satellite-based sensors and from other technologies are developed for detecting potential ocean acidification-related ecological changes over regional and basin-wide scales.
- Diverse genomic and molecular tools are developed for the *in situ* assessment of CO_2-sensitive physiological processes in different ecologically and economically important organisms.
- Mesocosm experiments and small-scale field experiments are conducted in diverse habitats. Free Ocean CO_2 Experiments (FOCE) are implemented and pilot-tested.
- Regional and global risks associated with OA and climate change are developed from model studies. Maximum atmospheric CO_2 levels that can sustain ecological functions of diverse marine ecosystems are determined.

Brief Bibliography of Reports and Reviews on Ocean Acidification

Doney SC, Fabry VJ, Feely RA, Kleypas JA (2009) Ocean acidification: the other CO_2 problem. *Ann. Rev. Mar. Sci.* 1: 169-192 (to be published Jan 2009; avail. online at http://arjournals.annualreviews.org/toc/marine/1/1).

Fabry VJ, Langdon C, Balch WM, Dickson AG, Feely RA, Hales B, Hutchins DA, Kleypas JA, Sabine CL (2008a) Present and Future Impacts of Ocean Acidification on Marine Ecosystems and Biogeochemical Cycles. Report of the Ocean Carbon and Biogeochemistry Scoping Workshop on Ocean Acidification Research, 9–11 October 2007, Scripps Inst. Oceanography, Univ. California, San Diego, CA

Fabry VJ, Seibel BA, Feely RA, Orr JC (2008b) Impacts of ocean acidification on marine fauna and ecosystem processes. *ICES J. Mar. Sci.,* 65: 414–432.

Guinotte, JM and Fabry VJ (2008) Ocean acidification and its potential effects on marine ecosystems. *Ann. New York Acad. Sci.* 1134: 320–342

Feely RA, Orr JC, Fabry VJ, Kleypas JA, Sabine CL, and Langdon C (in press) Present and future changes in seawater chemistry due to ocean acidification. In AGU Monograph, *The Science and Technology of CO_2 Sequestration*, B. J. McPherson and E. Sundquist, eds.

Kleypas JA, Feely RA, Fabry VJ, Langdon C, Sabine CL, Robbins LL (2006) Impacts of ocean acidification on coral reefs and other marine calcifiers: A guide for future research. Report of a workshop, 18-20 April 2005, St. Petersburg, FL, sponsored by NSF, NOAA, and U.S. Geol. Survey, 88 p.

NSTC Joint Subcommittee on Ocean Science and Technology (2007) Charting the Course for Ocean Science in the United States for the Next Decade, An Ocean Research Priorities Plan and Implementation Strategy, January 26, 2007, 84 p.

Royal Society (2005) Ocean acidification due to increasing atmospheric carbon dioxide, Policy Document 12/05. The Royal Society, London 57 p.

Schubert R, Schellnhuber H-J, Buchmann N, Epiney A, Grieβhammer R, Kulessa M, Messner D, Rahmstorf S, Schmid J (2006) The future oceans – warming up, rising high, turning sour, German Advisor Council on Global Change, Special Report, Berlin, 110 p.

Zeebe RE, Zachos JC, Caldeira K, and Tyrrell T (2008) Oceans: carbon emissions and acidification. *Science* (Perspectives), 321, 51-52, doi:10.1126/science.1159124.

Additional Sources of Information

EPOCA http://epoca-project.eu/

IMBER http://www.imber.info/

Ocean Carbon and Biogeochemistry (OCB) http://www.us-ocb.org/ and http://www.whoi.edu/sites/oceanacidification

JSOST (Joint Subcommittee on Ocean Science and Technology; National Science and Technology Council) http://ocean.ceq.gov/about/jsost.html

The Ocean Acidification Network: http://www.ocean-acidification.net/

National Academy of Sciences, Ocean Studies Board: http://www.nationalacademies.org/, http://dels.nas.edu/osb/

National Oceanic and Atmospheric Administration Ocean Acidification website http://www.pmel.noaa.gov/co2/OA/

Various Consensus Statements Regarding Ocean Acidification

European Geosciences Union Position Statement on Ocean Acidification http://www.egu.eu/statements/egu-position-statement-on-ocean-acidification.html

European Science Foundation Policy Briefing (28-30 Jan 2008)

International Society for Reef Studies (2008) Briefing Paper 5: Coral Reefs and Ocean Acidification

The Nature Conservancy and IUCN (2008) The Honolulu Declaration on Ocean Acidification and Reef Management, The World Conservation Union (IUCN), Gland, Switzerland

Australian Department of Climate Change and the Antarctic Climate & Ecosystems Cooperative Research Centre (Australia) "The Hobart Communiqué" (2008): Ocean Acidification: Australian Impacts in the Global Context