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REVIEW OF THE FEDERAL OCEAN ACIDIFICATION RESEARCH AND MONITORING PLAN

Committee on the Review of the National Ocean Acidification Research and Monitoring Plan

Ocean Studies Board

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
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Preface

Ocean acidification—the changes in carbonate chemistry and acidity (pH) of seawater resulting from entry of atmospheric CO_2 into the ocean—is an inevitable consequence of the rapid rate of CO_2 release into the atmosphere through anthropogenic activities like fossil fuel combustion. Atmospheric CO_2 concentrations are higher than they have been for at least 800,000 years, and the rate of release of CO_2 is the greatest for at least the past 55 million years. Since the start of the Industrial Revolution in the middle of the 18th century, atmospheric CO_2 levels have risen by ~40% and the pH of seawater has decreased by ~0.12 pH units, which corresponds to an approximately 30% rise in acidity. By the end of this century, models based on "business as usual" scenarios for CO_2 release predict a further decrease in pH that would lead to an approximately 100-150% rise in ocean acidity relative to the mid-18th century. Models show a continuing fall in seawater pH over the coming few centuries (if not longer), even though with rising CO_2 levels in seawater the capacity of the ocean to absorb additional CO_2 is diminished.

The consequences of ocean acidification—which is sometimes referred to as "the other CO_2 problem"—have received much less attention than CO_2's effects as a greenhouse gas. Whereas public acceptance of climate change is increasing rapidly, at the time of this writing polls indicate that less than ten percent of the U.S. public is even aware of the process of ocean acidification, much less concerned about its known or potential impacts. However, the effects of ocean acidification have become of increasing concern to a wide range of scientists over the past two decades.

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Three major international conferences on ocean acidification have been held, the most recent occurring in September 2012, during the preparation of our report. Presentations at this meeting, in conjunction with a proliferation of papers in the peer-reviewed literature, make it clear that ocean acidification is a multi-faceted problem whose impacts range from the physical chemistry of seawater to socioeconomic issues linked to acidification's effects on marine communities and fisheries. Whereas we have a deep understanding of the effects of CO_2 entry on the carbonate chemistry of the sea, as investigations extend to increasingly complex phenomena—from effects on individual species to consequences for ecosystems, fisheries, and economic systems dependent on marine life—fewer conclusions and predictions can be stated with high assurance about the near- and longer-term consequences of ocean acidification. As we point out in this document, recent studies of the biological effects of acidification have yielded some dramatic "surprises"—discoveries of critical effects that were completely unanticipated. Because the science of ocean acidification is in such an early stage of development, many more "surprises" are sure to be revealed, including new facets of acidification's effects on broad environmental and economic issues.

There is thus a well-recognized need—in the United States and internationally—for comprehensive programs that allow scientists and policy makers to predict the effects of ocean acidification on marine life, broadly defined, and on the social and economic systems that rely on a healthy ocean, whether for a source of protein (fisheries and aquaculture) or for physical protection (coral reef and shellfish systems that provide important barrier function against storms). This need has been recognized by Congress and many relevant Federal agencies for several years and appropriate planning efforts have been initiated. In 2009, Congress passed the Federal Ocean Acidification Research and Monitoring (FOARAM) Act, which mandates the creation of an integrated, multi-agency National Program on Ocean Acidification. Included in the mandates of the FOARAM Act was a requirement for formation of an Interagency Working Group on Ocean Acidification (IWGOA) to develop a *Strategic Plan for Federal Research and Monitoring of Ocean Acidification*. Per the requirements of the FOARAM Act, our committee was created as a vehicle for providing a constructive review of this Strategic Plan.

In the present document we offer a broad set of suggestions for improving the IWGOA's Strategic Draft Plan, which was released in March 2012, so as to enable a comprehensive, well-integrated, and cost-effective program to be evolved that can achieve the several mandates (Program Elements) found in the FOARAM Act. Our committee's composition, which included expertise in seawater chemistry, marine ecology, physiology, socioeconomics, and policy-development, mirrors the breadth

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of the Program Elements presented in the FOARAM Act and, therefore, in the Themes of the IWGOA's Strategic Plan. The analyses we present in this report involve both 'vertical' and 'horizontal' perspectives. In the former context, we have examined in depth the Strategic Plan's specific strategies for addressing the seven individual Themes found in the Plan. In the latter context, we have attempted to offer helpful suggestions for how these interrelated Themes can better be coordinated, such that, for example, findings from the natural sciences can effectively inform decisions related to mitigation and adaptation efforts in the realm of the socioeconomic challenges that will arise from ocean acidification.

As chair of the review committee, I wish to express my deep appreciation for the enormous level of effort expended by the committee and the National Research Council Staff who assisted us in all phases of our analysis. In my four decades of serving as a university faculty member, I have never worked with a committee that was so informed, cooperative, prompt to complete their tasks, and collegial throughout the whole process. For me (and I think I can speak here for the entire committee) it was remarkably educational to take part in discussions that ranged from the fine details of measuring the pH of seawater to the complex and difficult-to-predict effects of acidification on fisheries and the US and global economies. I thank the committee for being such a remarkable set of mentors! Special praise and expression of gratitude is warranted by the NRC staff who worked closely with us through all phases of our activities. Dr. Claudia Mengelt, the Study Director; Dr. Jessica Dutton, Research Associate; and Ms. Heather Chiarello, Senior Program Assistant, always knew when and how best to help us out. Dr. Susan Roberts, Director of the Ocean Studies Board, was always available to offer assistance on any challenging issue where our committee needed guidance.

Our committee hopes that this document will assist the IWGOA and other relevant parties in developing a comprehensive National Program in Ocean Acidification that meets the expectations of the FOARAM Act. A successful Program will help to provide our nation and the broader international community with a more complete understanding of the problems posed by ocean acidification and, through this analysis, will allow formulation of mechanisms for mitigating and adapting to this rapidly developing change in the our oceans.

Following NRC policy, our report was reviewed by nine expert referees. We thank these referees for their helpful suggestions, which reflect a reading of our report by "fresh sets of eyes" and well-informed perspectives on the great many topics encompassed by ocean acidification.

George Somero
Committee Chair

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Acknowledgments

This report was greatly enhanced by public input in advance and during the committee's meeting. The committee would like to thank those who were available to answer questions during the public meeting and prepare public comments. Specifically, the committee would like to recognize the information and answers provided by Cyndy Chandler, Woods Hole Oceanographic Institution. The written submissions and the public comments helped set the stage for fruitful discussions in the closed sessions that followed.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in their review of this report:

Ken Caldeira, Carnegie Institution of Washington (California)
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Lisa Suatoni, Natural Resources Defense Council (New York)

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by **Andrew Solow**, Woods Hole Oceanographic Institution, appointed by the Division on Earth and Life Studies, who was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Summary

Atmospheric carbon dioxide (CO_2) levels are currently approaching 395 ppm, a value that is 40% higher than those of the preindustrial period and exceeds CO_2 levels of at least the past 800,000 years. Perhaps more significant is the rapid rate of increase in atmospheric CO_2 concentration, a rate that is unprecedented over the last 55 million years of the Earth's history. The ocean plays a critical role in governing atmospheric CO_2 levels. By absorbing a substantial share of the CO_2 released through varied human activities, the ocean reduces atmospheric levels of this greenhouse gas and thus moderates human-induced climate change. However, this beneficial effect of CO_2 uptake by the ocean has resulted in potentially damaging consequences due to a lowering of ocean pH and related changes in ocean carbonate chemistry, collectively known as "ocean acidification."

Since the start of the Industrial Revolution in the mid-18th century, the average pH of the upper ocean has decreased by about 0.1 pH unit, corresponding to an approximately 30% rise in acidity, and is projected to decrease by an additional 0.3 to 0.4 units by the end of this century, corresponding to a 100 to 150% rise in acidity since preindustrial times. The current and expected magnitude and rate of ocean acidification argue for an expeditious and detailed investigation of ocean acidification and its associated impacts on ecosystems and natural resources. Additional environmental stressors—such as rising temperatures and decreases in dissolved oxygen—that may exacerbate the effects of acidification on marine organisms further highlight the urgency of this challenge. In par-

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ticular, understanding the effects of ocean acidification requires research on the changes in the chemical composition of seawater; the direct and indirect influences of ocean acidification on chemical, biological, and ecological processes; socioeconomic impacts; and the capacities of biological systems and human societies to adapt to the challenges arising from ocean acidification. This requires a multi-focused yet coordinated program that integrates knowledge about ocean acidification across the natural, social and economic sciences to provide a foundation for predicting the future consequences of acidification and for development of effective strategies to address these consequences.

Decreasing seawater pH has already been shown in laboratory experiments to have widespread influences on biological processes and numerous types of additional effects likely remain to be discovered. Many—and perhaps most—of these effects of acidification will have negative impacts on individual species and the ecosystems in which they are enmeshed. For example, ocean acidification decreases the availability of carbonate ions at calcification sites, making it increasingly difficult for many calcifying organisms such as corals, oysters, and calcifying phytoplankton to build their calcium carbonate skeletons and shells. However, calcifiers differ in their responses to ocean acidification, notably in the case of different species of reef-building corals. In contrast, some processes or certain species (e.g., photosynthetic carbon fixation in some plants), may benefit from rising CO_2 and bicarbonate levels. Disparity among species in responses to ocean acidification remains a critical unknown for efforts to predict what ocean acidification portends for marine life. In addition, many metabolic and cellular processes besides calcification and photosynthesis are affected by ocean acidification due to decreases in the pH of blood and cellular fluids. Falling pH can impede oxygen uptake by certain marine animals and directly or indirectly reduce metabolic rates.

The full suite of biological processes and structures perturbed by ocean acidification is difficult to predict. Some recently discovered effects of ocean acidification were wholly unanticipated. For example, laboratory studies of coral reef fish have revealed that neurological and behavioral processes can be affected by a decrease of seawater pH. These behavioral abnormalities may translate into changes in predator-prey interactions and capacities for locating suitable sites for settlement and recruitment.

Most of our knowledge of the effects of decreasing pH on marine organisms is from controlled laboratory and field mesocosm studies; we know much less about ocean acidification's effects on natural (or wild) communities and ecosystems. Thus, efforts are under way to extrapolate from controlled laboratory experiments and limited in situ observations to impacts at the community and ecosystem level. However, predicting the future consequences of ocean acidification for the marine environment

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and society is a challenging endeavor due to the complexity and dynamic nature of marine ecosystems and the likelihood that the effects of acidification will differ among species and ecosystems. Furthermore, interaction of stresses from acidification with other simultaneous stressors such as warming, eutrophication, and deoxygenation remains poorly understood.

Assessing the socioeconomic impacts from ocean acidification represents an even greater challenge. Globally, fish represented nearly 17% of society's animal protein intake in 2009 and 6.5% of all protein consumed and it is uncertain how ocean acidification will affect these resources. Although the broader potential socioeconomic impacts of ocean acidification are poorly known, impacts have already been observed on key industries like shellfish aquaculture. For example, the Pacific Northwest aquaculture industry, which is estimated to contribute approximately 270 million dollars per year and 3,200 jobs to local coastal communities, has recently experienced major failures in its oyster hatcheries due to effects of low pH waters on oyster larvae. Whereas these low pH values are due in large measure to upwelled water with low pH, the effects seen on larvae illustrate potential consequences of acidification resulting from entry of atmospheric CO_2 to the oceans. It is also important to point out that, at these sites in the Northwest and at other coastal sites influenced by runoff from land, effects of eutrophication on CO_2 content and pH are likely to be substantial. Thus, the effects of rising atmospheric CO_2 on pH are compounded by other anthropogenic influences. In response to threats posed by reduced pH (from any sources) some aquaculture operations are currently adapting their practices by monitoring pH changes in their water intake systems and timing water intake during favorable conditions. However, many other oyster farms lack the ability to monitor or predict such changes and will need to develop these capabilities. Many options to offset reduced pH and carbonate saturation in situations like oyster aquaculture (or other mariculture operations occurring around the globe) seem impractical due to the energy costs (and release of CO_2) associated with adding compounds like lime to increase pH.

The build-up of coral skeletons, which form the structural basis for coral reef ecosystems, is also pH-sensitive. These marine ecosystems support vast biodiversity and generate large amounts of dietary protein in the form of fish and shellfish, and provide physical protection from storms in coastal regions. Deep water coral communities serve as important nursery habitats for many species. How the direct and indirect effects of ocean acidification will translate into the health and sizes of fish and shellfish populations and, thereby, into food production, is an important but unanswered question in the broad arena of socioeconomic impacts of ocean acidification.

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STUDY'S ORIGIN AND THE COMMITTEE'S TASK

In 2009, Congress passed the Federal Ocean Acidification Research And Monitoring (FOARAM) Act (as part of PL 111-11), which directed an Interagency Working Group on Ocean Acidification (IWGOA) to design a National Ocean Acidification Program (referred to as the Program in this report) and develop a Strategic Plan for Federal Research and Monitoring of Ocean Acidification. The FOARAM Act also directs NOAA to request the National Research Council (NRC) convene a committee to review the IWGOA Strategic Plan. In particular, the NRC committee was asked to review the IWGOA Strategic Plan for federal research and monitoring on ocean acidification based on the program elements described in the FOARAM Act of 2009 and the advice provided to the IWGOA through the 2010 NRC report *Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean*. Specifically, the review committee was asked to consider the following elements: goals and objectives; metrics for evaluation; mechanisms for coordination, integration, and evaluation; means to transition research and observational elements to operational status; coordination with existing and developing national and international programs; and community input and external review (for full statement of task see Appendix A).

MAIN CONCLUSIONS FROM THE COMMITTEE'S REVIEW

The Strategic Plan presents a comprehensive framework for improving our understanding of ocean acidification, broadly defined to span the physical, chemical, biological, and socioeconomic sciences. It does an excellent job of covering the breadth of current understanding of ocean acidification and the range of research that will be required to advance a broadly focused and effective National Ocean Acidification Program. Because the committee's charge was to conduct a critical analysis of the Strategic Plan, the comments below focus on aspects of the Plan that could be improved, rather than on the Plan's many strengths.

The Strategic Plan follows the seven Themes laid out in the FOARAM Act. While these themes encapsulate the effort required to advance the understanding of ocean acidification, the Strategic Plan currently treats the themes largely as independent sets of activities without elaborating on how coordination among the agencies and integration of themes will be accomplished. While the committee recognizes that this is a strategic document and not an implementation plan, the Plan lacks sufficient detail on how objectives and goals will be reached and how the strategy will move toward implementation. The following modifications would remedy these shortcomings in the Strategic Plan:

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- Articulate a clear vision statement concerning ocean acidification in relation to the importance of ocean resources to society.
- Describe a process that would ensure better integration across the seven Themes and illustrate the interrelationships among the themes. More specifically, the various Themes describe important goals, but monitoring (Theme 1) and technology development (Theme 4) are required to advance research to understand responses to ocean acidification (Theme 2), modeling to predict changes and impacts on carbon cycle and ecosystems (Theme 3), and assessment of socioeconomic impacts (Theme 5). To better communicate the rationale and importance of the National Ocean Acidification Program, the goals and rationale for the various activities in each Theme need to be better integrated across the Themes and stated upfront. For example, research on socioeconomic impacts and societal adaptation is presented in isolation and the description implies that such research could be postponed until impacts on organisms and ecosystems are better known. However, the priority research questions in the socioeconomic Theme ought to be used to define and drive, where appropriate, priorities and research questions in the natural sciences, and therefore the socioeconomic priorities need to be better integrated into the other themes.
- Specify a mechanism for coordination among federal agencies and with other ocean acidification efforts in the U.S. and abroad. Currently, the Strategic Plan does not specify the roles of the individual agencies nor does it describe a process for coordination among the agencies to ensure that resources are used in a cost-effective manner, without unnecessary duplication, to strategically address priority research goals.
- Describe a process and criteria by which the IWGOA will set priorities within and among themes. The current draft of the Strategic Plan provides a comprehensive list of research goals to be accomplished by the National Ocean Acidification Program, but neither sets priorities nor explains how priorities will be established as part of the implementation plan. The process for setting priorities needs a mechanism to ensure broad stakeholder participation.
- Develop a process for periodic reevaluation of priorities, including metrics to evaluate progress toward the Program's goals. Such metrics will be needed for the IWGOA to report on the Program's progress every two years as required by the FOARAM Act. These progress reports could be used by the IWGOA to refine its strategy for the renewal of the Strategic Plan in 5 years, as called for in the FOARAM Act. Much remains to be learned about ocean acidification and critical new and unconventional research needs may appear as studies move forward. Thus, it is critical to build flexibility into the Program to allow for innovation, ongoing evaluation, and iterative adjustments in Program priorities and direction.

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The committee commends the IWGOA for calling out the need for a National Ocean Acidification Program Office (referred to as the National Program Office in this report) and agrees strongly with the Strategic Plan that this office will be central to the successful implementation of the Program. The committee recommends that the plan provide greater clarity regarding the creation, function, and governance of the National Program Office. Although the Strategic Plan gives the National Program Office the responsibility for developing the implementation plan, it does not explain how or when the National Program Office will be set up. Therefore, a plan for the creation, function, and governance of the National Program Office is essential for the timely development of the implementation plan.

Based on previous experiences with national research efforts, the following functions are fundamental for a successful program office:

- coordinating research across the federal and state agencies;
- coordinating activities with international efforts;
- engaging the broader stakeholder community in developing research priorities and metrics for evaluating progress;
- communicating important results among agencies, policy makers, stakeholders, and the public; and
- ensuring that the nation receives the highest return from its investment in the National Ocean Acidification Program.

Many models exist for the structure and governance of program offices. The committee views the following aspects as important to an effective program office: independence from any single federal agency and the ability of successfully gaining the buy-in and commitment from various stakeholders—such as the research community, affected industries, non-federal agencies, and nongovernmental organizations. An independent National Ocean Acidification Program Office could help engage all stakeholders in developing processes to guide the priorities of the diverse activities described in the Strategic Plan. The National Program Office will be the foundation and catalyst for a successful National Ocean Acidification Program.

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1

Introduction

Although large fluctuations in atmospheric CO_2 levels are common in Earth's history, past increases in CO_2 occurred over periods of hundreds of thousands to millions of years, and thus differ considerably from the very rapid present day increase related to human activities. The current rate of increase in the level of atmospheric carbon dioxide is unprecedented over at least the past 55 million years (Kump et al., 2009; Zeebe et al., 2009). The rate is far greater than occurred in even the most rapid events known from Earth history, and each of these past events were accompanied by important changes in ocean chemistry and mass extinctions of ocean or terrestrial life or both. Currently, atmospheric CO_2 levels are approaching 395 ppm, a value 40% higher than the preindustrial period and greater than has occurred for at least 800,000 years. Approximately one-third of the CO_2 added to the atmosphere since the beginning of the Industrial Revolution in the mid-18th century has been absorbed by the ocean, and recent estimates suggest that the ocean is continuing to absorb each year approximately one-quarter of global anthropogenic CO_2 emissions (Sabine et al., 2004; Khatiwala et al., 2009; Le Quéré et al., 2009; Sabine and Tanhua 2010). By absorbing a substantial share of the CO_2 released through such human activities as fossil fuel combustion, cement production and land-use change, the ocean plays a critical role in moderating human-induced climate change. However, this beneficial effect of CO_2 uptake by the ocean is coupled with potentially damaging consequences due to changes in ocean carbonate chemistry and

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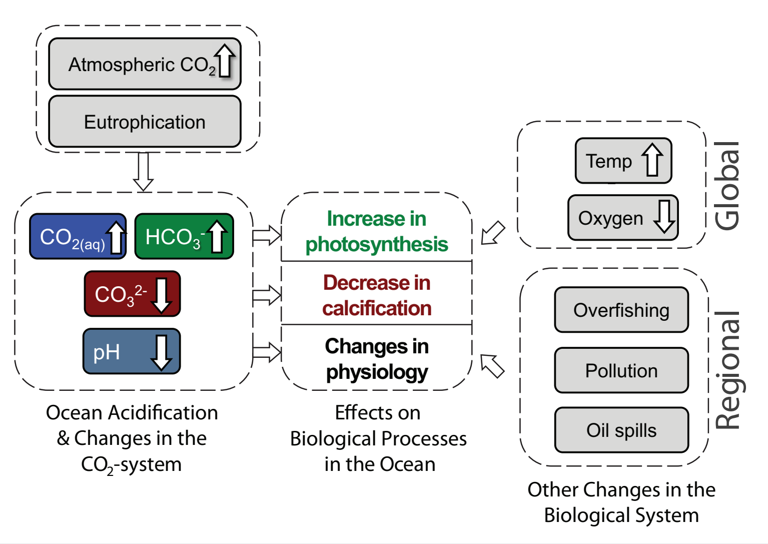
BOX 1.1
Ocean Acidification

Definition and Drivers of Ocean Acidification: Acidity is measured using the pH scale, where pH is the negative of the base 10 logarithm of hydrogen ion activity. Note that ocean acidification does not necessarily mean that seawater will become acidic, i.e., attain a pH below 7. Rather, it refers to the increase in hydrogen ion activity and thus the lowering of pH from any point on the pH scale.

The expression "ocean acidification" has been defined in somewhat different ways in the literature. It is important to differentiate between pH reduction due to natural processes like volcanic activity and sea floor CO_2 venting and acidification due to anthropogenic activities that result in rapid increases in atmospheric CO_2 levels. The Committee adopts the definition of Field et al. (2011) that was developed at an IPCC workshop on ocean acidification: **"Ocean acidification refers**



SOURCE: Adapted from Kleypas, 2012 (unpublished presentation).

pH; processes collectively termed "ocean acidification" (see definitions in Box 1.1).[1]

To date, global warming has been the primary focus of public interest and scientific investigation concerning effects of CO_2 emissions. Ocean

[1] Because the rate of increase is more rapid than in the past, sources and sinks of alkalinity are no longer in balance, and both ocean pH and $CaCO_3$ saturation are changing in the ocean (Hönisch et al., 2012)

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to a reduction in the pH of the ocean over an extended period, typically decades or longer, which is caused primarily by uptake of carbon dioxide from the atmosphere, but can also be caused by other chemical additions or subtractions from the ocean Anthropogenic ocean acidification refers to the component of pH reduction that is caused by human activity."

Ocean Acidification and Changes in the CO_2 and Carbonate System: Atmospheric carbon dioxide is absorbed by the ocean, where it reacts with seawater to form carbonic acid, which then dissociates to form bicarbonate ions (HCO_3^-) and hydrogen ions (H^+). The increase in hydrogen ion activity (decrease in pH) is buffered by the carbonate system: some of the added hydrogen ions react with carbonate ions (CO_3^{2-}) to form more bicarbonate, which makes CO_3^{2-} less abundant. If atmospheric carbon dioxide rises slowly, ocean pH and carbonate ion levels will remain relatively stable due to dissolution of existing calcium carbonate deposits in the ocean (1,000s+ of years), weathering of terrestrial rock (100,000s+ of years), and tectonic processes (millions of years). However, the current rapid rise in atmospheric CO_2 is faster than the time required for natural processes to buffer changes in the ocean carbonate system and avoid large changes in pH or ocean carbonate levels. Increased nutrient input from runoff can result in larger than usual algal blooms (i.e., eutrophication) that produce organic matter, which contributes to increases in CO_2 when respired.

Effects on Biological Processes: The increase in CO_2 and HCO_3^- availability has the potential to increase photosynthesis by some but not all photosynthesizers in the ocean. The decreased availability of CO_3^{2-} at calcification sites makes it more difficult for many types of calcifying organisms, including some phytoplankton, corals and bivalves (clams and mussels) to build their calcareous shells or skeletons. Lastly, a decrease in pH may cause important physiological changes, many of which are associated with negative impacts such as increased energetic costs for regulating internal H^+ concentrations.

Simultaneous Changes Impacting Biological Processes: Global increase in ocean temperature and decrease in dissolved oxygen are stressors for many marine organisms that will likely add to or amplify the impacts of ocean acidification, resulting in changes in the composition, abundance, and production of biological communities. In addition, regional human impacts—such as overfishing, eutrophication, pollution, or oil spills to name a few—also affect biological processes.

acidification is generally unknown to the public and has been the subject of substantially less scientific research than have the effects of CO_2 on climate. However, the relative lack of attention given to ocean acidification belies its potential importance as a threat to marine organisms, ecosystems, and socioeconomic activities dependent on a healthy ocean (e.g., IPCC, 2011, Caldeira and Wickett, 2003; Gattuso and Hansson, 2011). A few key background data and the interactions illustrated in Box 1.1 help

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to more clearly define the contributors to ocean acidification and put its consequences for marine life and human societies into perspective.

Since the beginning of the Industrial Revolution, the average pH of the upper ocean has decreased by about 0.1 pH unit, which corresponds to an approximately 30% rise in acidity (activity of hydrogen ions (H^+)). Shallow ocean pH is projected to decrease by an additional 0.2-0.3 pH units by the end of this century, corresponding to a rise in acidity of 100-150% since the mid-18th century (IPCC, 2007 WGI; under the IS92a scenario). The rates of relevant chemical change in deep waters may not necessarily be that much slower than in surface waters because deeper waters naturally have higher concentrations of inorganic carbon, a lower buffer capacity, and are thus more susceptible to CO_2 perturbations. This rate of acidification is faster than any rates inferred from the geological record for at least the past 55 million years (Zeebe and Ridgwell, 2011; Hönisch et al., 2012). Due to the mixing of ocean waters across depths, pH is decreasing—and will continue to decrease—in deeper regions of the marine water column as well as at shallow depths.

These changes in pH and carbonate chemistry are expected to have effects on marine organisms at all levels of biological organization, including the physiologies of individual organisms and the composition, productivity, and health of diverse marine ecosystems. Furthermore, the effects of ocean acidification may be compounded by stresses arising from other features of global change, notably rising temperatures and decreases in concentrations of dissolved oxygen. Currently, we are in the early stages of discovering what these diverse and interacting effects are and how they may affect marine ecosystems and the socioeconomic activities that depend on ocean-derived resources. However, even though the field of ocean acidification research is relatively new, it is growing rapidly and beginning to reveal the scope and magnitude of biological, ecological, and societal consequences projected to arise from future acidification. Early studies focused primarily on the many organisms that build shells and skeletons of calcium carbonate, such as reef-building corals and the small calcareous phytoplankton that lie at the base of the marine food web. Recent studies now illustrate that the biological impacts of ocean acidification go far beyond calcification processes and also include photosynthesis, respiration, nutrient acquisition, behavior, growth, reproduction, and survival per se (Gattuso et al., 2011).

Some discoveries of how acidification affects marine species have been unanticipated. For example, it was recently discovered that low pH impairs sensory and neurotransmitter systems of larval marine fish, which leads to maladaptive changes in their behavior and olfactory capabilities (Munday et al., 2009; Nilsson et al., 2012). It seems reasonable to

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conclude that other unanticipated effects of acidification will be revealed as scientific research on this topic continues.

Whereas much remains to be learned about the scope and magnitude of the consequences of ocean acidification, existing data support a growing consensus in the research community that most documented responses to acidification reflect impairment of physiological capacity or performance. Certain physiological processes in some species may benefit from ocean acidification (e.g., enhancement of photosynthesis in sea grasses and some algae by increased levels of CO_2 [Kroeker et al., 2010]). However, the beneficial effects on some species may directly lead to negative effects on other species in the same marine community (Kroeker et al., 2010).

Although our knowledge about the biological effects of ocean acidification is expanding quite rapidly, most of this research has either involved studies of single species under closely controlled laboratory conditions, or mesocosm-studies in which communities of organisms are confined under controlled conditions. Much remains to be learned about the effects of ocean acidification on natural ecosystems, but moving from laboratory and mesocosm experiments toward assessments and projections of the in situ, long-term responses of ecosystems presents not only scientific challenges, but logistical and financial ones as well. Simply extrapolating information on impacts from laboratory-derived species' responses or short-term in situ observations (Gattuso and Riebesell, 2011) is hampered by the variability in the responses across species, and even within some single species. Lastly, as mentioned earlier, projecting long-term changes in marine ecosystems is complicated by the interactions of impacts due to ocean acidification with those resulting from alterations in water temperature and oxygen concentration or from other human activities (e.g., from agricultural run-off and extractive activities).

Socioeconomic impacts of ocean acidification are likely to be substantial, based, for example, on the dependence of humans on protein from marine species (approximately 6.5% of dietary protein in 2009) (FAO, 2012). However, projecting socioeconomic impacts of ocean acidification is currently challenging because of a dearth of research in this domain. Nonetheless, economically important natural resources may already be affected by ocean acidification resulting from upwelling events and, to a lesser extent, from increases in dissolved atmospheric CO_2. For example, the Pacific Northwest Aquaculture industry, which is estimated to contribute approximately 270 million dollars per year and 3,200 jobs to local coastal communities, has recently experienced major failures in its oyster hatcheries due to effects of upwelling of low pH seawater on oyster larvae (Washington State Blue Ribbon Panel, 2012). In addition, complex ecological effects of low pH on coral reefs have been documented, notably

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in studies of natural CO_2 seeps where sharp pH gradients exist across an ecosystem (Fabricius et al., 2011). Effects of decreasing pH on coral reefs are likely to be amplified by influences of additional stressors such as increases in water temperature (Anthony et al., 2008) or run-off. Coral reefs are not only important in supporting healthy fisheries (Jones et al., 2004) but also support a vital tourist industry and can serve as important physical barriers to reduce the effects of storms on coastal communities.

In summary, the magnitude and rate of change in pH and the marine carbonate system and the likelihood that this change—in conjunction with climate change and other human impacts on the ocean—will have wide-ranging biological and socioeconomic effects argue for a comprehensive and integrated program to broaden our understanding of the scope of ocean acidification and its potential consequences for ocean ecosystems and society. The program's purview needs to encompass such diverse activities as monitoring ongoing changes in carbonate chemistry and pH of seawater as well as associated changes in marine life; elucidating the fundamental physiological effects of acidification on diverse marine species, ranging from primary producers to animals higher in the trophic web; analyzing and predicting—with assistance from well-designed models—how ecosystems will change under acidification (and climate change); and predicting the socioeconomic consequences of acidification and how these impacts can most effectively be prevented or ameliorated. Only a broad and closely coordinated research and monitoring program supported by multiple federal agencies and that interacts effectively with relevant international programs will be able to deal with these complex and interacting facets of ocean acidification in a comprehensive and cost-effective manner.

1.1 POLICY CONTEXT

Congress recognized the potential seriousness of the ocean acidification issue several years ago and mandated that the issue receive sufficient study to enable the development of an effective research and monitoring program. In the Magnuson-Stevens Fishery Conservation and Management Reauthorization Act of 2006 (PL 109-479 sec 701), Congress asked the NRC to conduct a comprehensive study on ocean acidification. The resulting report (*Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean* [NRC, 2010]) summarized the latest scientific understanding of the issue and described the necessary elements of a national ocean acidification program (NRC, 2010).

While the NRC 2010 study leading to this report was under way, Congress in 2009 passed the Federal Ocean Acidification Research And Monitoring (FOARAM) Act (as part of PL 111-11). In October 2009, as man-

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dated by the Act, the Subcommittee on Ocean Science and Technology (SOST) established the Interagency Working Group on Ocean Acidification (IWGOA), which includes representatives from the National Oceanic and Atmospheric Administration (NOAA), National Science Foundation (NSF), Bureau of Ocean Energy Management (BOEM), Department of State (DOS), Environmental Protection Agency (EPA), National Aeronautics and Space Administration (NASA), U.S. Fish and Wildlife Service (USFWS), U.S. Geological Survey (USGS), and the U.S. Navy. The group has been meeting regularly and has drafted the Strategic Plan for Federal Research and Monitoring of Ocean Acidification (from here on referred to as the Strategic Plan). As described in the FOARAM Act, the goals of the Strategic Plan are to "*advance the understanding of ocean acidification and its physical, chemical, and biological impact;*" and to "*improve the ability to assess the socioeconomic impacts of ocean acidification; and provide information for the development of adaptation and mitigation strategies.*" The Strategic Plan is to include five program elements: (1) monitoring of ocean chemistry and biological impacts associated with ocean acidification; (2) research to understand impacts on marine organisms and food webs and to track marine ecosystem responses; (3) modeling to predict changes in biogeochemical cycles and ecosystems; (4) technology development; and (5) assessment of socioeconomic impacts of ocean acidification and development of adaptation and mitigation strategies. The FOARAM Act also directs NOAA to request a review by the NRC of the Strategic Plan. Our report is the response to this charge (see committee's task below).

The draft Strategic Plan was submitted to the Office of Science and Technology Policy (OSTP) for review in the summer of 2011 and was approved by OSTP in May 2012. The draft Strategic Plan was published for public comment in June of 2012. The creation of the Strategic Plan for Federal Research and Monitoring of Ocean Acidification, following the mandates of the FOARAM Act, represents an important next step forward in the development of a comprehensive, integrated, and cost-effective program for examining the diverse facets of ocean acidification.

1.2 THE COMMITTEE'S TASK

As indicated in the previous section, our committee was asked to review the IWGOA Strategic Plan for Federal Research and Monitoring on Ocean Acidification based on the Program Elements described in the FOARAM Act of 2009 and the advice provided to the IWGOA through the 2010 NRC report, *Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean.* More specifically, the review is to consider the following elements: goals and objectives; metrics for evaluation; mechanisms for coordination, integration, and evaluation; means to transition

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research and observational elements to operational status; coordination with existing and developing national and international programs; and community input and external review.

1.3 REPORT ROADMAP

In the following chapters, our report analyzes the extent to which the seven Themes of the IWGOA Strategic Plan address the mandates of the FOARAM Act. During its review, the committee identified several common issues that arose across most, if not all, of the Themes of the Strategic Plan. These issues include the establishment of a National Ocean Acidification Program Office, the prioritization of research and monitoring efforts, and the development of metrics for evaluating the success of the different programs. These key issues are briefly discussed and summarized in Chapter 2, to provide a context for the more detailed and focused analysis that occurs in Chapter 3, where the committee reviews the seven individual Themes that comprise the core of the Strategic Plan.

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2

General Issues: Content and Comprehensiveness of the IWGOA Strategic Plan

In this chapter, the committee summarizes the most important issues that emerged from the review of each of the seven Themes and apply broadly to the Strategic Plan as a whole. The committee also notes certain editorial issues observed among all Themes, for example, problematic or inconsistent use of terminology in some contexts (see Appendix C), and the style or order of the material presented. However, these issues are of secondary importance in our analysis and we thus refrain from further elaboration on these concerns; they can readily be addressed in a revised Strategic Plan. Instead, the following discussion focuses on concerns about more substantive elements of the Strategic Plan: vision statement, goals and objectives, research priorities and metrics, strategy for implementation, and National Program Office. The committee considers these to be typical elements of a strategic plan and the Interagency Working Group on Ocean Acidification (IWGOA)'s Strategic Plan would benefit from strengthening each of these elements and improving, where relevant, integration among them.

To aid in its review of the IWGOA's Strategic Plan, the committee examined other examples of strategic research plans such as the U.S. Global Change Research Program's (USGCRP's)[1] strategic plans (Climate

[1] The U.S. Global Change Research Program (USGCRP) is a multiagency program formed in response to the Global Change Research Act of 1990. The USGCRP has a national program office and dedicated national program office staff to manage the process of coordination across the agencies, the periodic assessment of the research results, and the strategic planning process. The USGCRP was called the U.S. Climate Change Science Program under the G. W. Bush Administration, but is again called the USGCRP under the current administra-

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Change Science Program Strategic Plan [CCSP] 2002, USGCRP Strategic Plan 2012) along with a National Research Council review of the CCSP's 2002 strategic plan (NRC, 2004). Strategic plans have become a requirement of the GPRA Modernization Act of 2010 and the Office of Management and Budget provides guidance for preparing and submitting an agency strategic plan (OMB Circular No A-11 2011). Based on these documents, the committee found that the following elements are generally included in a federal strategic research plan: a vision or mission statement, goals and objectives, research priorities or criteria for setting priorities, metrics for evaluation of progress and success, and a strategy for implementation of the goals and objectives of the plan. In the context of this last element, the committee is cognizant of the importance of distinguishing a strategic plan from an implementation plan, but also recognizes that there is overlap in content between a strategic and an implementation plan. Thus, several of the committee's analyses center on the issue of how the Strategic Plan can lay out a process to ensure that the different objectives can most effectively be implemented.

As follows, the committee discusses the IWGOA's Strategic Plan vis-à-vis the five elements of a strategic plan. The chapter concludes with a discussion of the National Ocean Acidification Program and the National Ocean Acidification Program Office, the latter of which is a critical conduit to the implementation of the Strategic Plan.

2.1 VISION AND MISSION STATEMENT

The committee found no clear 'vision' or 'mission' statement in the Strategic Plan. OMB Circular A-11 (see Section 210, page 2) specifies the structure of a strategic plan and is concerned with how a strategic plan reflects the 'vision' or 'mission statement' of an individual agency. The committee acknowledges the difficulty in framing a single mission statement that reflects the diversity of agencies involved, each representing a different mission. However, the committee believes that a concise vision or mission statement of the type found in the USGCRP Strategic Plan[2] (2012; page 11) would assist, in particular, the nonspecialist reader in appreciating the thrust and importance of the Strategic Plan.

RECOMMENDATION: The Strategic Plan should include a vision statement for the National Ocean Acidification Program.

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tion. This program and its origin are similar to the National Ocean Acidification Program; and thus, serves as a good example for how a strategic plan and associated metrics can be developed.

[2] "***Vision:*** *A Nation, globally engaged and guided by science, meeting the challenges of climate and global change.*" (USGCRP Strategic Plan, 2012)

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2.2 GOALS AND OBJECTIVES

The ten-year Strategic Plan prepared by the IWGOA is comprehensive in describing critical research and monitoring goals for the near- and long-term for seven different, but often closely interrelated, Themes. The Themes of the Strategic Plan include the five Program Elements required by the FOARAM Act and two additional Themes that are critical for the success of an overall research and monitoring program in ocean acidification. Each Theme in the Strategic Plan presents goals and objectives with a description of the rationales for their inclusion in the Plan. The committee's review of the goals and objectives for each Theme is presented in detail in Chapter 3. At this juncture, the committee emphasizes two overarching points related to goals and objectives that apply to all Themes and are of key importance for the Strategic Plan.

First, the goals and objectives could be strengthened if they included a more integrated and comprehensive treatment across themes. This is particularly true in the context of how the natural and social sciences and monitoring components of the overall program will inform important societal questions such as food security and conservation. As discussed further in the context of the individual Themes, advancing the social sciences (e.g., research on socioeconomic impacts, adaptation, and conservation) cannot be placed on hold while the natural sciences and monitoring progress. Rather, socioeconomic goals and objectives need to be an integral part of the focus at the same time and coordinated with the natural science and monitoring efforts. This concern can be addressed by including in the appropriate Theme sections how the goals of each Theme relate to the social sciences (e.g., socioeconomic impacts, adaptation, and conservation strategies).

Second, the committee identified another common shortcoming in the Plan's descriptions of goals: the absence of clear priorities (or a strategy for establishing priorities) for undertaking the varied efforts needed to implement the goals and attain the Plan's objectives. This concern is discussed in the following section.

RECOMMENDATION: The Strategic Plan should describe a process that can ensure integration across the themes, coordination among the agencies, and development of priorities.

2.3 RESEARCH PRIORITIES AND METRICS

A strategic plan ideally defines the process by which priorities will be set. The long list of research and monitoring goals in the Strategic Plan is divided into short-term and long-term goals for each Theme, but does not prioritize the goals or provide criteria for doing this. Examples of

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criteria include scientific and societal importance (both intrinsic to one Theme and interrelated with other Themes), logic of research sequence, evaluation of the costs and benefits, and the availability of human expertise, research infrastructure, and funding. Many frameworks for setting research criteria are available in published reports.

A National Research Council review of *Charting the Course of Ocean Science in the United States for the Next Decade: An Ocean Research Priorities Plan and Implementation Strategy* (NRC, 2007) proposed the following questions to identify its priorities:

- *Is the proposed research transformational (e.g., will the proposed research enable significant advances in insight and application, even with potentially high risk for its success; would success provide dramatic benefits for the nation)?*
- *Does the proposed research impact many societal theme areas?*
- *Does the research address high-priority needs of resource managers?*
- *Would the research provide understanding of high value to the broader scientific community?*
- *Will the research promote partnerships to expand the nation's capabilities (e.g., contributions from other partners, including communities outside of ocean science, such as health science; unique timing of activities)?*
- *Does the research serve to contribute to or enhance the leadership of the United States in ocean science?*
- *Does the research contribute to a greater understanding of ocean issues at a global scale?*
- *Does the research address mandates of governing entities (federal agencies; state, tribal, and local governments)?*

As indicated above, clear societally relevant objectives could provide one important focus for development of a framework for the National Ocean Acidification Program. Such a framework could help set priorities of the social and natural science research to inform the development of solutions to problems (see Box 2.1 for an example). Framing research goals through the lens of societal needs when relevant could also help determine the appropriate allocation of resources across the different Themes and research goals.

Setting priorities is not only important to ensuring that important societal needs are met, it is also critical when the broad goals of the Strategic Plan are juxtaposed with the realities of federal funding. Although the FOARAM Act specifies a ten-year program, the Plan describes the fiscal resources available to achieve its goals only for the President's budget for a single year, FY 12. As Figure 2.1 reveals, the majority of the funding allocation is focused on Theme 1 (monitoring) and Theme 2 (research on ocean acidification impacts), $9.65 million and $14.43 million respectively.

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BOX 2.1
An Example for Setting Priorities Based on Societal Relevance

The Strategic Plan might postulate ‘food security’ as an important societal question and regard research focused on answering this question to be of high priority. For example, how can the U.S. ensure the future of a sustainable source of domestic seafood of high quality and affordability? This question would require thinking about the role of commercially wild-caught and aquaculture sources of seafood and the different potential impacts that ocean acidification would have on these sources. While natural scientists would strive to improve the understanding of direct and indirect impacts of ocean acidification on the biology of these fisheries (as outlined in Themes 1, 2, and 3), social scientists and economists would want to consider the societal preferences for the relative contribution of both sources (given their environmental footprints) to supply healthy and affordable seafood (as part of Theme 3 and 5).

In the wild-caught fishery, the indirect effects (e.g., less primary prey available through food webs) are likely to be more significant relative to the direct effects (e.g., higher natural mortality rates) and information will be needed on a scale commensurate with the ecosystem and management. These impacts could lead to a delay in the recovery of a particular fish stock. Thus, understanding management practices that could incorporate information about the direct and indirect environmental impacts on the rebuilding of fish stocks would emerge as a high priority research goal.

In the aquaculture setting, the research could focus on the direct effects on farmed species or in developing predictions of acidity on a local scale that can help aquaculture operations avoid exposing their stocks to unfavorable conditions. If it is the latter, scientists might need to advance the understanding of how accurate the predictions need to be. That is, the societal gain from better forecasts could be marginal if the increased precision does not translate into improved aquaculture practices and aquaculture yield.

Theme 3 (modeling) and 4 (technology development and standardization of measurements) receive funds on the order of $2-3 million, whereas Themes 5 and 6 are each funded below $1 million. In fact, if funds available for research on the socioeconomics and adaptation measures remain at their current levels, only a single small research project could be supported for a year; this is unlikely to generate the kind of innovation required to develop ways to adapt to the impacts of ocean acidification. Similarly, budget allocations of $152,000 for data management will not allow for a substantial effort. Input from the research community and other stakeholders could help facilitate future adjustment of the total resources available for the seven Themes as well as define a process for prioritizing among the Themes.

If the IWGOA aims to achieve all goals outlined in its Strategic Plan

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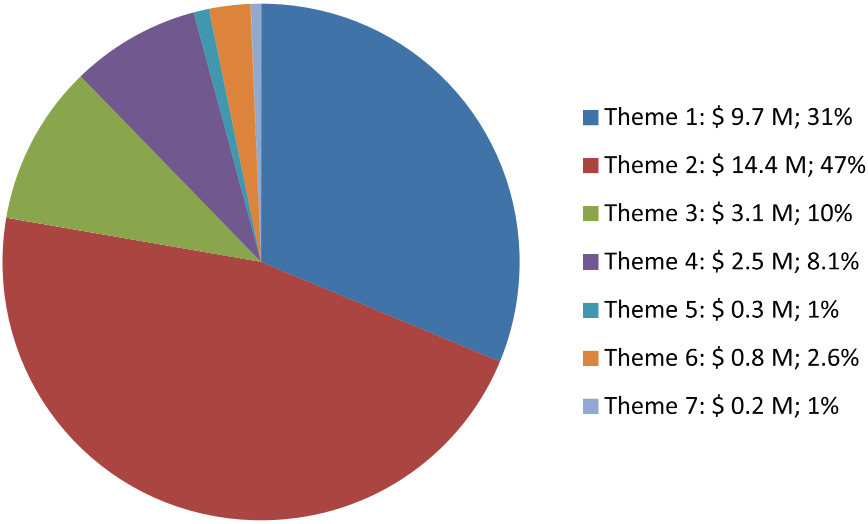

FIGURE 2.1 Funding levels in the President's FY 2012 Request and associated with each Theme of the Strategic Plan. Theme 1: Monitoring of Ocean Chemistry and Biological Impacts; Theme 2: Research to Understand Responses to Ocean Acidification; Theme 3: Modeling to Predict Changes in the Ocean Carbon Cycle and Impacts on Marine Ecosystems and Organisms; Theme 4: Technology Development and Standardization of Measurements; Theme 5: Assessment of Socioeconomic Impacts and Development of Strategies to Conserve Marine Organisms and Ecosystems; Theme 6: Education, Outreach, and Engagement Strategy on Ocean Acidification; Theme 7: Data Management and Integration.

by the end of the 10 years, new resources would be needed (see Box 2.2). However, constrained federal budgets might make it difficult to mobilize resources at the required level, therefore requiring the IWGOA to set some priorities among the listed goals. This potential scenario further illustrates the benefit of describing a clear process for setting priorities. Such a process could be facilitated, at least in general terms, by information about the likely costs of the activities associated with different goals. Using such information, the feasibility of pursuing the listed goals within a short or long time frame could be assessed. In setting priorities, it will be critical to establish a process that can engage the views of the extramural research community and the stakeholders in general. In addition, the committee concludes that a National Program Office (see next section) would be critical in the process for setting priorities using criteria set forth in the Strategic Plan. To inform this process, the National Program Office could convene representatives from the extramural research community (for

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example, through an external advisory committee including social and natural scientists).

The committee was also asked to consider, as part of its review, the metrics[3] that would be employed to evaluate progress toward the goals outlined in the seven Themes. The thematic sections in the Strategic Plan do not provide an explicit description of the metrics for evaluation, thus the committee found this component of its task particularly challenging.

Since issuance of the Government Performance and Results Act (GPRA) of 1993 and related Office of Management and Budget (OMB) policies, agencies have increased efforts to establish metrics and track progress (NRC, 2005). However, it is often difficult to evaluate research using strictly quantitative measures because the discovery process is complex and outcomes that matter to society are not always traceable to specific projects; these achievements often result from a combination of research findings and their use in formulating policy. Most agencies, therefore, rely on expert peer review to assess progress in research (NRC, 2005). Performance measures are also agency-specific and may include qualitative outputs or outcomes (see Box 2.3 for additional details). For example, NOAA's National Marine Fisheries Service might use the reduction in numbers of overfished major stocks while NSF might need more general input or output metrics. Therefore, a broad range of metrics need to be used and they need to be tailored to the specific research goals and agency missions.

The FOARAM Act requires the National Ocean Acidification Program to provide biennial progress reports and a revised 10-year plan every 5 years. This requirement dictates that progress of the various elements of the program be evaluated. To this end, it is important that metrics be established to measure progress toward the Strategic Plan's goals, and that these evaluations of the program be used to set priorities in an iterative fashion. The committee recognizes the difficulty in establishing a set of specific metrics for scientific research. It is also recognized that the Strategic Plan is not an implementation plan, which would be a more appropriate document to provide a detailed description of metrics for evaluation. However, there are many reports (NRC, 2005) that provide guidance on developing such performance measures. For example, the committee finds that many of the suggested metrics for the former CCSP, now referred to as the USGCRP, could be applied to the Ocean Acidification Program (NRC, 2005).

Lastly, the issues of "metrics" and "prioritization" are closely linked. As stated in the 2005 NRC Report, *Thinking Strategically: The Appropriate*

[3] Government agencies use "metrics" (synonymous with "performance measures") to assess progress toward pre-established goals (NRC, 2005).

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BOX 2.2
Federal Funding Needs for Ocean Acidification (based on a report by the National Marine Sanctuaries Foundation)

A report by the National Marine Sanctuaries Foundation (NMSF) assesses whether the current investments in ocean acidification research are commensurate with the urgency and magnitude of the challenge. The NMSF's report compares current funding levels with two estimates of the funding needed for ocean acidification research and monitoring (see Figure). One such estimate is based on informal conversations with program managers at various federal agencies (red squares) and a second set of estimates was provided by the Ocean Carbon and Biochemistry (OCB) program's white paper. In this white paper, OCB estimates that a U.S. National Ocean Acidification Program would need $50-100 million per year to provide timely information for decision-makers (blue circles).

The green squares in the figure display actual combined funding spent on ocean acidification related research by several federal agencies (i.e., EPA, MMS/BOEM, NASA, NOAA, USGS, NSF) (IWGOA, 2011; IWGOA report draft). NOAA and NSF's combined actual spending exceeds what the FOARAM Act authorized to be appropriated for these two agencies. The FOARAM Act authorizes the following sums to be appropriated to NOAA: $8 M for FY10; $12 M for FY11; $15 M for FY12; and $20 M for FY13. To NSF, the FOARAM act authorized $6 M for FY10; $8 M for FY11; $12 M for FY12; and $15 M for FY13. However, what Congress appropriated for each year (NOAA, for example, $5.5 M for FY10, $6.3 M for FY11, $6.2 M for FY12) was significantly lower than what they were authorized to appropriate.

Use of Metrics for the Climate Change Science Program, it is important to realize *"the potential to use metrics not just as simple measures of progress, but as tools to guide strategic planning and foster future progress."* Evaluating progress and setting priorities both benefit from using an expert peer-review process.

RECOMMENDATION: The Strategic Plan should define a process by which the goals will be prioritized, because not all the goals listed in the Strategic Plan are equally important for achieving the scientific mandates of the FOARAM Act. These priorities should be re-evaluated as part of the 5-year revision of the Strategic Plan. This re-evaluation of priorities could be informed by the progress evaluation, based on metrics set forth by the Strategic Plan.

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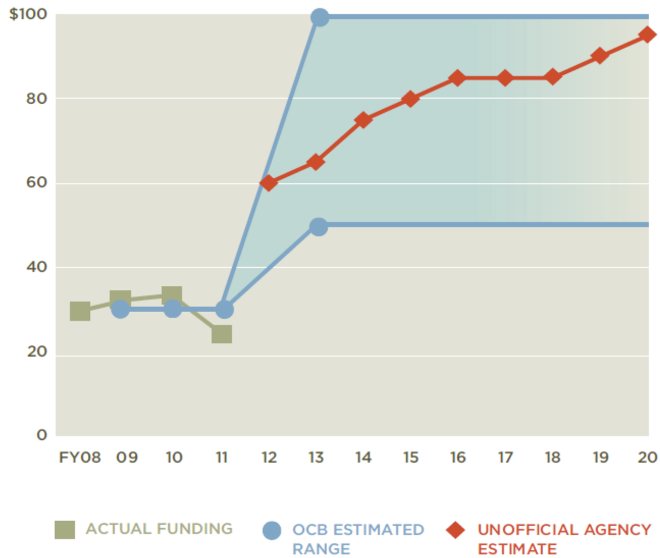
FIGURE 1. ACTUAL FUNDING AND FUTURE PROJECTED INVESTMENT NEEDS FOR FEDERAL OA RESEARCH AND MONITORING (in millions of dollars)



* We selected FY09 as the start date for the OCB estimates because the white paper was published in 2009, and because federal funding in FY09–FY11 was already approximately in the $30 million range estimated as needed for the start-up period.

SOURCE: Reprinted with permission from Cutting Edge Design (from NMSF, 2012).

2.4 STRATEGY FOR IMPLEMENTATION

The Strategic Plan is lacking detail about strategies for implementation with the exception of mentioning that the National Ocean Acidification Program Office "*serve the vital role of developing and executing an implementation plan.*"[4] Elements to be described in a strategy for implementation may include criteria and process for prioritization (see above), individual priorities and responsibilities for each agency, a process for ensuring coordination and integration across the Themes and research disciplines, and an approach for establishment of the National Program Office. Without a clear definition of the structure of the National Pro-

[4] IWGOA Strategic Plan, pg. 3.

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BOX 2.3

The NRC report *Thinking Strategically* categorizes metrics in the following way (and uses the discovery of the Antarctic Ozone hole as an illustrative example):

"**Process**—a course of action taken to achieve a goal. (Example metrics include existence of a project champion and length of time between starting the research and delivering an assessment on stratospheric ozone depletion to policy makers.)

Input—tangible quantities put into a process to achieve a goal. (An example input metric is expenditures for (a) theoretical and laboratory studies on ozone production and destruction, (b) development and deployment of sensors to sample the stratosphere, (c) modeling and analysis of data, or (d) meetings and publications.)

Output—products and services delivered. (Examples of output metrics include number of models that take into account new findings on chlorofluorocarbon chemistry or number of publications and news reports on the cause of stratospheric ozone depletion and its possible consequences.)

Outcome—results that stem from use of the outputs. Unlike output measures, outcomes refer to an event or condition that is external to the program and is of direct importance to the intended beneficiaries (e.g., scientists, agency managers, policy makers, other stakeholders). (Examples of outcome metrics are the number of alternative refrigerants introduced to society to reduce the loss of stratospheric ozone and scientific outputs integrated into a new understanding of the causes of the Antarctic ozone hole.)

Impact—the effect that an outcome has on something else. Impact metrics are outcomes that focus on long-term societal, economic, or environmental consequences. (Examples of impact metrics include the recovery of stratospheric ozone resulting from implementation of the Montreal Protocol and related policies and the increase in public understanding of the causes and consequences of ozone loss.)"

SOURCE: NRC, 2005.

gram Office and the functions it will provide, the implementation of this Strategic Plan might be delayed and made more difficult.

The Strategic Plan lacks a description of the appropriate roles of the various Federal agencies in implementing the specified goals. While this kind of specificity would seem to belong in an implementation plan, such a description of how the federal agencies can strategize to leverage resources and find synergies given their complementary missions would increase the likely success of the implementation of the Strategic Plan.

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RECOMMENDATION: If the Strategic Plan is to "establish the National Ocean Acidification Program" as instructed by the FOARAM Act, it should strengthen the discussion of the National Program and its mission and, as stressed in the section below, provide greater details on how the National Ocean Acidification Program and the Program Office will be established.

2.5 NATIONAL PROGRAM OFFICE

The committee is in full agreement with the Strategic Plan's assessment that a National Program Office is essential to ensure that ocean acidification research is well coordinated across all the participating federal agencies, and to provide a national voice for effective international cooperation. In addition, the committee feels strongly that the National Program Office should not be perceived as being associated with a single federal agency and that (ultimately) coordination would be improved if it was the sole U.S. office responsible for coordinating ocean acidification activities. The National Program Office could be part of the federal government structure, similar to the U.S. GCRP, or be modeled after program offices such as the GLOBEC (Global Ocean Ecosystem Dynamics) or U.S. JGOFS (Joint Global Ocean Flux Study) program offices that reside within academic institutions. The committee also endorses the statement in the Strategic Plan that the National Program Office be subject to oversight from the IWGOA. In addition, the committee concludes that it is equally important that a process be established for the National Program Office to receive external advice, such as an external scientific steering committee, that is focused explicitly on the activities of the office.

The committee recognizes that the costs of setting up and operating such an office require resources that might otherwise be directed at research. The currently limited budget dedicated to the National Ocean Acidification Program exacerbates this drain on dedicated funds for ocean acidification research. However, the committee views establishing an office as an important investment in ensuring that the U.S. has an effective National Ocean Acidification Program. This is particularly important given the broad array of Themes and assuming that future budgets of the National Ocean Acidification Program will grow. Strong coordination across the Themes and between agencies through a single National Program Office will maximize efficiency and avoid wasting resources through needless duplication of activities. The cost could potentially be minimized if it remained part of the federal government, with agencies lending staff time to such an office. Furthermore, its staff size could be adjusted based on the size of the overall National Ocean Acidification Program. Alternatively, if the National Program Office is to reside at an

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academic institution, it might be collocated with an already existing program office. In addition, the National Program Office will—through the various activities outlined on pg. 9 of the Strategic Plan—ensure that there is continuing effective community input into the evolving strategies and goals as the Program moves forward.

In developing the design of a National Program Office in the Strategic Plan, the IWGOA can draw on many lessons learned from previous, highly successful programs (and program offices) such as the GLOBEC Program and the U.S. JGOFS Program (NRC, 2010) and federal program offices such as the USGRCRP. Based on lessons learned from previous national research programs, the following functions are fundamental for a successful program office:

- coordinating research across the federal and state agencies;
- coordinating activities with international efforts;
- engaging the broader stakeholder community in developing research priorities and metrics for evaluating progress;
- communicating important results among agencies, policy makers, stakeholders, and the public; and
- ensuring that the nation receives the highest return from its investment in the National Ocean Acidification Program.

RECOMMENDATION: The Strategic Plan should provide clarity regarding the creation, function, and governance of the National Program Office.

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3

Specific Analysis of the Themes of the Strategic Plan

This chapter provides the committee's review of each Theme described in the Strategic Plan. The general issues discussed in Chapter 2—notably the points concerning establishment of a National Program Office, prioritization of activities, metrics for evaluating progress, and implementation of program elements—are further addressed below in the specific contexts of the seven Themes. As emphasized in Chapter 2, the committee recognizes that a strategic plan differs from a more focused implementation plan, and that detailed descriptions of specific programs for achieving the broad goals of the FOARAM Act cannot be developed in the Strategic Plan. Nonetheless, the committee concludes that some of the Themes provide insufficient information regarding the design of effective mechanisms for successful implementation. Thus, the committee offers recommendations for each Theme to guide implementation efforts.

The committee analyzes each of the seven Themes by, first, summarizing the relevant mandate (Program Element) from the FOARAM Act and, then, discussing how effectively the goals of the Program Element are addressed by the Theme in the Strategic Plan. Recommendations are offered when the committee concludes that the Strategic Plan needs further development.

Our committee recognizes that considerable time has elapsed between completion of the Strategic Plan and initiation of the review process. During this period, new literature has appeared, some of which needs to be analyzed and integrated into the Strategic Plan. We offer several suggestions for these up-dates in our critiques of the different Themes.

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Overall, the committee concludes that the Strategic Plan is a well-researched, logically developed, and well-written document.[1] With appropriate modification, the committee believes that it will serve to make a compelling case for the implementation of a program on ocean acidification research and monitoring that satisfies the mandates given in the FOARAM Act.

THEME 1: MONITORING OF OCEAN CHEMISTRY AND BIOLOGICAL IMPACTS

The FOARAM Act (page 9) mandates "*[m]onitoring of ocean chemistry and biological impacts associated with ocean acidification at selected coastal and open-ocean monitoring stations, including satellite-based monitoring to characterize (A) marine ecosystems; (B) changes in marine productivity; and (C) changes in surface ocean chemistry.*" To this end, the IWGOA Strategic Plan's Theme 1 addresses how the U.S. scientific community will go about monitoring changes in ocean chemistry and its biological impacts. The committee finds that the focus of Theme 1 overlaps considerably with that of Theme 2 ("*Research to understand the species-specific physiological responses . . . impacts on marine food webs . . . and . . . ecosystem responses to ocean acidification.*"), such that close attention to developing integrated and complementary efforts across these two Themes is warranted. Likewise, the critical role of advances in technology for monitoring efforts, as pointed out in Theme 4, makes improved integration of Themes 1 and 4 appropriate.

The treatment of the relevant FOARAM Act Program Element specific to Theme 1 is well-presented and comprehensive, especially in the arena of chemistry and efforts to monitor pH and carbon-related variables (see below). These monitoring efforts are very important and it is critical that they be expanded rapidly, because for many coastal waters no baseline information exists. The monitoring activities outlined in Theme 1 will provide the first descriptions of the carbonate chemistry and its variability of these coastal waters. These measurements are important because they will form the baseline against which future changes will be measured and provide information about the coastal environment that supports many U.S. fishery resources.

Because the rationale for these monitoring efforts is not presented in detail until Theme 2, a nonexpert reader would not fully grasp the importance and reasons for monitoring from the description presented in

[1] Note: The report does not offer recommendations that involve syntax and grammar. The Strategic Plan is generally well-written and we feel that the revision process will enable the Strategic Plan's authors to remedy any shortfalls in expositional writing that may currently exist.

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Theme 1. To make the Strategic Plan more effective in conveying the need for monitoring and for adequate support for these efforts, the rationale for the chemical monitoring effort along U.S. coasts needs to be better described in Theme 1 or the order of Themes 1 and 2 needs to be reversed. For instance, the importance of early detection of changes in pH is notable, because such 'early warning' information would be needed for ecological and socioeconomic analyses. And, as in the case of other types of studies outlined in the Strategic Plan, monitoring activities require prioritization; no clear process for establishing priorities is given in Theme 1.

The committee commends the IWGOA for providing relevant examples of how ocean acidification monitoring can be built into existing research programs at relatively low cost. The CLIVAR/Repeat Hydrography program and the time-series programs at Hawaii and Bermuda are highlighted. These programs provide what are probably the best available examples of efforts for monitoring seawater carbonate chemistry over time. However, the limitations in temporal and spatial sampling seen in existing studies reflect the need for a greatly expanded monitoring program, one whose success is likely to depend on new technology (e.g., improved in situ sensors). The time-series programs provide the additional advantage of biological monitoring being integrated with the chemical studies. The National Science Foundation (NSF) Long-Term Ecological Research program is another example of an existing activity that could be augmented to include chemical and biological monitoring related to ocean acidification.

Theme 1 of the Strategic Plan provides a good description of the chemical parameters that need to be measured and points out that particulate inorganic carbon (PIC), particulate organic carbon (POC) and dissolved organic carbon (DOC) need to also be included in the suite of parameters that are monitored. The Strategic Plan could be strengthened by better distinguishing the different objectives of monitoring the chemical parameters and by stating how the technologies and sampling protocols should be selected to best achieve these different objectives.

One objective is the detection of long-term trends in a data record against a background of substantial short-term variability. Achieving such a goal requires high instrument and measurement precision and an adequate length of data record. Ideally, in situ sensors could play a central role in long-term monitoring efforts because this type of instrumentation could be placed at a large number of sites around the globe to obtain records of pH-related variables at different depths with high temporal resolution. However, until in situ sensors have the needed precision, accuracy, and long-term stability, the collection and analysis of discrete samples will be vital to ensure that the carbonate chemistry data sets will have the accuracy required to detect trends in carbonate chemistry in response to ocean acidification. The Strategic Plan's emphasis on in situ sensors

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is warranted over the longer term, but the current sensors available for such monitoring have significant limitations (e.g., in terms of continual calibration during long-term periods of data collection). The committee is encouraged, however, by reports that development of in situ sensors with adequate precision, stability, and depth-capabilities is progressing rapidly, in part through effective collaborations between academic, governmental and industrial organizations. Here, the development of CTD sensors serves as a model for such collaborations. The development of adequate sensors and their deployment at numerous sites would represent a major breakthrough in monitoring efforts. Lastly, whatever technology and methods of data collection happen to be used, the long-term utility of data sets will depend on consistent, accurate calibration protocols, to ensure comparability of data over time (see Dickson et al., 2007).

A second objective is to measure short-term variability at appropriate temporal and spatial scales, to understand the range of values organisms are exposed to and to complement in situ biological observations to study organisms' responses to such changes. Examples of this type of monitoring include changes in pH and carbonate chemistry due to physical processes such as upwelling events, as well as biological processes such as diurnal cycles in photosynthesis and respiration. For these purposes, in situ sensors are highly attractive because they offer the ability to sample more frequently in space and time.

A significant weakness in the presentation of Theme 1 is the lack of detail about proposed biological monitoring. This shortfall is due in part to the fact that much remains to be learned about which biological processes are most sensitive to changes in carbonate chemistry, how ocean acidification will impact different organisms across their life cycles, and, ultimately, how these diverse interspecific and life stage-specific sensitivities will play out through species interactions at the ecosystem level. This research need is in part captured by those goals in the Strategic Plan that state the need to "*develop biological monitoring protocols.*" There is a growing recognition in the scientific community that a universal set of biological parameters may not exist, but rather that the optimal biological parameters to characterize the effects of ocean acidification may be specific to particular habitats or even organisms.

Consequently, the committee agrees with the following statement in the Strategic Plan: *"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)."* The committee further believes that a determination of what is monitored, how it is measured, and the usefulness of these measures in detecting biological responses to ocean acidification will be a rapidly evolving aspect of the Ocean Acidification Program. Thus, the committee believes it is important that the Plan

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describe a process for reevaluating the inventory of biological measurements chosen for monitoring purposes (for example, building from the experience of the process studies detailed in Theme 2).

In developing a strategy for creating an ocean acidification observing network, it is important to maintain a broad perspective of not only how the chemical and biological monitoring advances the scientific needs, but also the suite of socioeconomic issues that may result from the diverse effects of ocean acidification on marine ecosystems (presented in Theme 5). As mentioned throughout this committee's report, such an interdisciplinary approach should be incorporated at the very early stages of the evolving U.S. Ocean Acidification Program, to ensure that development of effective policies (e.g., in "adaptation;" see Theme 5) are commensurate with research on ocean acidification's impacts, and that the program helps familiarize the public at large about the potential impacts of ocean acidification on U.S. economic interests (an issue treated in Theme 6).

The Strategic Plan does not provide much information on the physical locations of monitoring sites nor the frequency of monitoring at the chosen locations. Criteria for decision making on choices of monitoring sites and frequencies of monitoring will be crucial to the success of the overall monitoring effort. Although some decision on monitoring locations may be based on practical considerations, such as the existence of laboratory and ship facilities in an area, it is critical that the goals of the FOARAM Act serve as guides for implementing a broad monitoring program. Thus, for example, the coastal sites to be monitored should include waters where commercially important shellfish occur either naturally or in mariculture facilities. Monitoring in these regions would help in integrating monitoring efforts with socioeconomic concerns. Frequency of monitoring is also a critical element in the design of a monitoring program. Continuous monitoring may be needed in situations where intermittent upwelling of low pH waters threatens shellfish mariculture operations. Additionally, although various coastal regions will experience differing impacts, it appears conjectural in the discussion of Theme 1 to state at the onset of the program that one region is more threatened than another. Some regions are strongly predicted to be at risk, but at present there are too few data to support predictions regarding the degree of vulnerability for most coastal areas.[2] Nonetheless, the discussion in Theme 1 could emphasize important observing sites located in U.S. territorial waters (perhaps using

[2] Vulnerability is a function of exposure, sensitivity, and adaptive capacity (i.e., the capacity to cope with or recover from an environmental stressor). Resource managers are urged to assess the vulnerability of the systems they are charged with managing and information that can inform such vulnerability assessments will be critical for adaptation planning (NRC, 2010). Such vulnerability assessments can also assist in planning research and monitoring activities.

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a more detailed map than Figure 5 of the Strategic Plan), that are relevant to vital marine resources and to U.S. economic interests.

Finally, as is the case for all Themes—and as is discussed in depth in Chapter 2—there is a lack of information concerning *prioritization* of the different activities that are proposed and the *metrics* that would be used to evaluate how effectively different research and monitoring activities are moving toward realization of the program goals.

In summary: To convey more effectively the rationale for chemical and biological monitoring, the Strategic Plan needs to describe at the beginning the potential consequences of ocean acidification and the importance of monitoring for tracking ocean acidification-related changes in marine chemistry and biology. In addition, an explicit description of the various purposes for monitoring the chemical parameters would improve the Strategic Plan. The role of evolving technology, notably for in situ measurements, must be taken into account to ensure that the most powerful new methods are integrated into monitoring programs. Thus, integration of Themes 1 and 4 is important. Because the biological parameters to be monitored will likely evolve with an increasing understanding of the impacts, it is important that the Strategic Plan describe a process for reevaluating the inventory of biological measurements chosen for monitoring purposes. Themes 1 and 2 therefore should be integrated. Lastly, monitoring should also include the socioeconomic information needed to address the societal challenges related to ocean acidification (Theme 5).

THEME 2: RESEARCH TO UNDERSTAND RESPONSES TO OCEAN ACIDIFICATION

The FOARAM Act mandates "*[r]esearch to understand the species specific physiological responses of marine organisms to ocean acidification, impacts on marine food webs of ocean acidification, and to develop environmental and ecological indices that track marine ecosystem responses to ocean acidification.*" This broad Program Element of the Act encompasses the wide impacts of ocean acidification and the tasks described herein are closely related to activities essential for achieving goals presented in many of the other Themes in the Strategic Plan. Thus, in the analysis below we focus not only on the extent to which the Strategic Plan addresses its primary Element of the FOARAM Act, but also on how well it integrates Theme 2 with the other relevant Themes.

The goals in this section of the Strategic Plan are consistent with the requirements of the FOARAM Act, as well as the many previous reports that were used as resources for developing the Plan. Given the complexities of organismal physiology and ecosystem structure and function,

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Theme 2 of the Strategic Plan necessarily deals with many research challenges and thus includes many recommendations and research goals. The chapter is comprehensive and covers a broad array of ocean acidification impacts across scales of ecology (species to ecosystems) and time (including geological), as well as the research techniques required to address the diverse questions comprising this complex Theme.

The Strategic Plan has done a good job of summarizing the state of knowledge within a rapidly growing field. However, since the Strategic Plan was written, the original literature on ocean acidification has grown considerably. It therefore is necessary to revise the text and the list of references accordingly, to ensure that recommendations and goals are based on the most current information available in the literature. As follows, the committee makes a series of suggestions concerning literature references to reflect new developments that could be used to update and strengthen Theme 2:

- Consider including more references that represent international research.
- Reconsider use of references that are out-of-date and, therefore, may present conclusions that have been supplanted by more recent work (e.g., McNeil et al., 2004); in this case, a recent reference by Shaw et al. (2012) is more appropriate.
- Reconsider the balance of references related to impacts of ocean acidification, such that calcification receives appropriate but not undue emphasis. As indicated in Chapter 1, recent studies have demonstrated the wide-ranging effects of ocean acidification on organismal function, including unanticipated effects on behavior, olfaction, and neurotransmitter action in marine fish (Simpson et al., 2011; Briffa et al., 2012; Nilsson et al., 2012). A widely occurring consequence of ocean acidification involves energy costs involved in regulation of pH values of body fluids (Pörtner et al., 2010). In many, if not most animals, costs of pH regulation may rise as ocean pH decreases. An increasing number of studies are focusing on this energetic cost of pH regulation and it deserves greater attention in this Theme. Interaction of ocean acidification with other global change-related stresses needs to be mentioned (see Pörtner et al., 2010). Pörtner et al. (2010) has introduced a conceptual model that suggests that elevated CO_2 (and reduced O_2) can reduce the thermal tolerance of species exactly at a time when they are being challenged by thermal stress.
- Huesemann et al. (2002) and Millero et al. (2009) on page 21 of the Strategic Plan do not seem to support the statements made.
- The discussions on natural CO_2 seeps and Free Ocean CO_2 Enrichment (FOCE) are out of date; updating and addition of recent references would improve this discussion. Figure 6 does not represent ocean acidifi-

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cation; rather, a figure from Fabricius et al. (2011), an important reference that is missing from the document, would be much better (see example Figure 3.1 below).

The overall approach in Theme 2 concerning biological adaptation could be developed in a more focused manner and key terms could be defined to reduce ambiguity. In the latter context, the various uses of the terms "adaptation" and "adapt" need to be defined. All organisms will exhibit some capacity to adapt, but there is a need to understand the time frame (individual lifetime versus multiple generations) and the limits of this capacity (both rates and magnitude; for review, see Somero, 2012). A clear distinction needs to be stated between the capacity to "*acclimatize/ acclimate*," which refers to phenotypic changes during an organism's life-

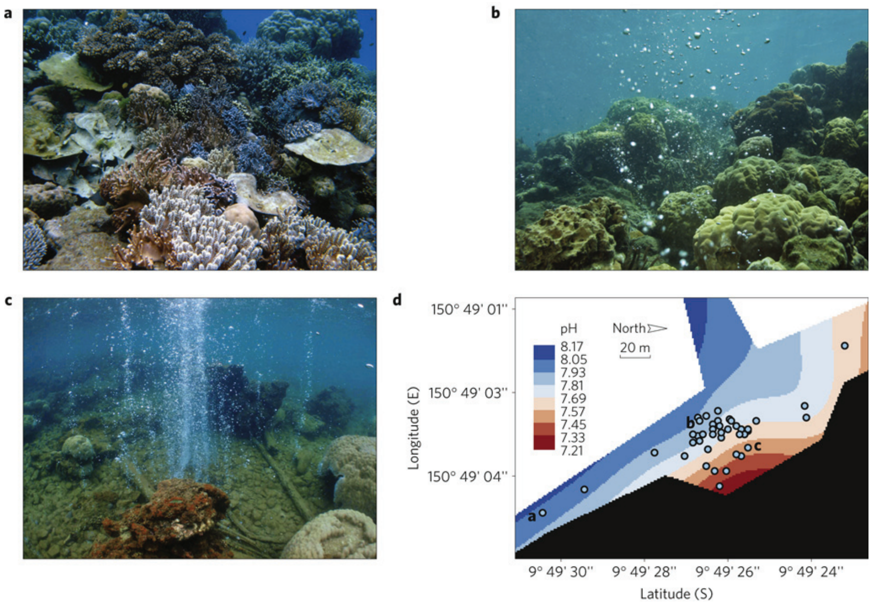

FIGURE 3.1 Volcanic CO_2 seeps of Milne Bay, Papua New Guinea, showing seascapes at **a**, control site ('low pCO_2': pH~8.1), **b**, moderate seeps ('high pCO_2': pH 7.8–8.0), and **c**, the most intense vents (pH <7.7), showing progressive loss of diversity and structural complexity with increasing pCO_2. **d**, Map of the main seep site along the western shore of Upa-Upasina; color contours indicate seawater pH, and the letters indicate the approximate locations of seascapes as shown in **a**-**c**.
SOURCE: Reprinted with permission from Macmillan Publishers Ltd.: Nature Climate Change, Fabricius et al. (2011).

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time, and "*adaptation*" which in the evolutionary sense involves genetic changes. The potential for acclimatization may be critical in conferring short-term tolerance to ocean acidification during a species' lifetime (e.g., during diurnal or seasonal fluctuations in pH found in tide pools and kelp forests). Likewise, acclimatization to factors such as temperature and oxygen content that may co-vary with pH may be critically important. However, the ultimate success of a species in coping with ocean acidification over longer multigenerational time scales may demand genetic adaptation. Species with shorter generation times are likely to have greater abilities to evolve adaptive changes than species with long generation times, assuming adequate genetic variation exists. Related to the latter, currently little is known about differences between species or among populations of a single species in tolerance of reduced pH; this area of research merits vigorous study to identify the potential adaptive capacities of different marine species in the face of ocean acidification.

The analysis in Theme 2 would benefit from a broader consideration of the types of nonbiological chemical effects relevant to biogeochemical cycles and ecosystem function. Although the FOARAM Act's mandate for Theme 2 is focused chiefly on organismal and ecological effects of ocean acidification, many of these effects are closely coupled with the influences of ocean acidification on nonliving processes. Thus, one notable gap within this Theme is the lack of attention given to the chemical effects of acidification. Besides a discussion of the influence on element availability to phytoplankton, there is very little presented in Theme 2 about how acidification might affect chemical properties of detrital particles, or processes like sorption or flocculation, which are very important in coastal and open-ocean waters. Sorption of many elements and compounds on natural particles is greatly affected by pH (Millero, 2009). Trace metal speciation, bioavailability and toxicity are influenced by pH. These effects of ocean acidification, which remain poorly understood, could influence the physiologies of individual organisms and the broader ecological responses to falling pH. Thus, the analysis needs to also include the types of chemical effects mentioned above, that is, the characteristics of detrital material important in nutrient cycling and diets (especially of species associated with the detrital particles), the physical processes of flocculation/disaggregation and their effects on marine particle dynamics.

The IWGOA is commended for its recommendations to include paleo-studies and data synthesis. Theme 2 notes that paleo-studies can yield important insights about conditions that caused ocean acidification in the geologic past, and the associated marine biological responses. This section could benefit from a brief mention of past ocean acidification events and their causes, with references to the key publications. It should also mention the value of Earth system modeling in understanding past ocean

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acidification events. Data synthesis speaks to the importance of using the best, standardized methods in research so that valid comparisons can be made among studies.

Understanding the broad biological effects of ocean acidification, including the influences of other environmental factors like temperature on acidification's impacts, will strongly benefit from promotion of investigations into ocean acidification's effects on community and ecosystem structure and function. Studies done in the laboratory or in the field using mesocosms may be inadequate for making predictions of effects of acidification on natural ecosystems and communities. In large measure, a primary shortcoming of controlled (laboratory or mesocosm) studies is that, by focusing on only pH (and pH-related variables in the carbonate system), the influences of other factors like rising temperature and eutrophication that can influence responses to acidification may be missed. Whereas it is commonly difficult to tease apart effects of, say, falling pH and rising temperature, field studies of natural ecosystems that examine the full spectrum of environmental changes are needed to generate realistic understandings of global change and to support predictions of future shifts in community and ecosystem structure, many of which may have important socioeconomic consequences. The understanding and monitoring of ecosystem responses to ocean acidification are still in their infancy, and the Strategic Plan includes an appropriate emphasis on expansion of this research topic

An additional balancing of research approaches is required when decisions are made about the types and numbers of different species to be studied. The Strategic Plan recognizes this point when it contrasts emphasis on breadth versus depth of focus (i.e., the distinction between studies of "*an expanding list of species rather than focusing resources on in depth studies of a narrow group of species*"). In reality these two approaches are driven by different questions. "*In-depth*" analyses of single species are needed to elucidate the basic physiological and molecular mechanisms involved in stress from and adaptation to acidification. This mechanistic analysis is critical for elucidating the exact nature of physiological perturbation from acidification and other stressors related to global change. Examination of an "*expanded list of species*" will of course be needed to evaluate interspecific differences in effects of ocean acidification, to allow predictions of effects at the community and ecosystem levels of biological organization to be developed. In particular, comparative studies will be important to examine the difference in responses among closely related species. For example, wide differences in capacities to regulate pH at sites of calcification were found among reef-building corals, thereby allowing some, but not all species potentially to reduce the effects of acidification (McCulloch et al., 2012). Different forms of calcium carbonate structural materials

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(calcite, aragonite and magnesium-rich calcite, in order of increasing sensitivity to low pH) are used by different organisms. Therefore, to evaluate the differential sensitivities of calcium carbonate-utilizing species to ocean acidification, comparative studies should take into account the types of carbonate employed by different phytoplankton and animals. Because these two lines of investigation—mechanistic and comparative—are both necessary and, ideally, complementary, there is a need to judiciously allocate resources to both types of study and define priorities.

In the context of research scope and priorities, the committee believes that there is an imbalance in the emphasis given to different types of physiological processes and the effects that ocean acidification may have on these biological processes. As pointed out above in the context of imbalance in the literature citations, there is an overemphasis on calcifying organisms. This overemphasis reflects the past research focus on calcification, which is by now the most studied of the impacts of ocean acidification. Although calcification is a critically sensitive physiological process for many taxa, many other key physiological processes (e.g., nitrogen fixation, photosynthesis, respiration, and behavior) are affected by ocean acidification in ways that affect non-calcifiers as well as calcifiers (Gattuso and Hansson, 2011). A more balanced program that incorporates studies on the lesser known effects of ocean acidification thus is needed.

As mentioned above, it is important to evaluate the effects of ocean acidification at all levels of biological organization, and the Strategic Plan concurs with this perspective. The recommendation to study '*other factors*' in addition to physiological processes could also be expanded to emphasize the need for information that will enable a scaling-up from single species to population and community levels. The value of measuring organisms' responses to ocean acidification, especially when studies incorporate effects of other factors and environmental stressors, is greatly increased when they provide key parameters for population and community models. Although physiological and behavioral studies can yield insights into the state of health of individual organisms, it is critical to incorporate analyses of rates of growth, survival, and reproduction of individuals, as well as analyses of effects on predation and competition, because data from these measurements can potentially be translated to rates of biomass production and demographic status for populations. Such measures can be essential for developing ecosystem models, including models focused on fisheries-related issues of socioeconomic importance.

This Theme does a comprehensive job of outlining sets of 3- to 5-year and 10-year goals for the National Ocean Acidification Program. The discussion of goals reflects a good summary of proposals found in previous reports and papers. To be consistent with previous reports, however, some of the 10-year goals need to be addressed sooner in the Program. As

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mentioned in Chapter 2, this Theme would benefit from a prioritization process to assess the most important goals to advance.

In summary: The discussion of calcification and other physiological processes in the *Species-Specific Physiological Responses* section would benefit from a more balanced representation of the multiple physiological processes that could be affected by acidification. This section thus needs to be expanded to recommend studies on the impacts of ocean acidification and other simultaneous environmental changes on organism *performance and its key physiological underpinnings*, rather than overemphasizing research on calcification processes. The Strategic Plan needs to include a description of research goals that (1) ensure that research addresses key knowledge gaps, (2) investigate the potential for physiological acclimatization and examine evolutionary mechanisms for adaptation to maintain or increase ecosystem resilience, (3) study how effects of ocean acidification interact with those of other stressors, and (4) examine how changes at the organism level will alter ecosystem structure and function. These goals will likely promote the integration of experimental and observational results (Themes 1 and 2) with physiological and ecological models (see Theme 3).

THEME 3: MODELING TO PREDICT CHANGES IN THE OCEAN CARBON CYCLE AND IMPACTS ON MARINE ECOSYSTEMS AND ORGANISMS

The FOARAM Act includes 'modeling' as a Program Element, "*to predict changes in the ocean carbon cycle as a function of carbon dioxide and atmosphere-induced changes in temperature, ocean circulation, biogeochemistry, ecosystem and terrestrial input, and modeling to determine impacts on marine ecosystems and individual marine organisms.*"

The introduction to Theme 3 (page 27 of the Strategic Plan) provides a summary of the current status of the field of modeling and highlights some challenges, along with an appreciation of its current and future evolution. This section presents a fair amount of information, although it is not always sufficiently supported by literature references. The section falls short, however, in describing how these model developments will contribute to reaching the main objectives outlined in this particular Program Element of the FOARAM Act and, more generally, how modeling studies can help to achieve the broader objectives of the FOARAM Act. In the latter context, there is inadequate integration of modeling with the other Themes in the Plan.

To strengthen the Strategic Plan, the committee believes that Theme 3 could be improved if it identified how models can contribute to ocean

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acidification research at present and with what level of certainty (see Box 3.1).

The scope of modeling activities listed in the Strategic Plan is broad, ranging from process-based understanding (level of the individual cell to organisms) to broader-scale biogeochemical functions (e.g., primary production, carbonate production, etc.) to impact assessments including socioeconomic analyses. Similarly, the Strategic Plan discusses model studies that span phenomena over large scales in time and space. Scale appears as a central issue to modeling in both biological and physical domains. The structure of this section would be improved by categorizing along scales specific to the target processes or questions. Furthermore,

BOX 3.1
How Models Can Contribute to Ocean Acidification Research

Modeling studies serve in a range of ways to advance ocean acidification research. Modeling can be a tool for using in situ observations and experimental results to develop predictive algorithms that can be used to test hypotheses in an iterative and integrative fashion. Modeling is iterative because models evolve in response to new observational data. Modeling can also be used to synthesis and integrate data to bridge scales, in several different contexts: scales can be biological (e.g., from the scale of the single cell to the organism, the population, and the community), physical, (e.g., from the localized time series station to the ocean basin and beyond), and temporal (e.g., models can be run to simulate interannual variability or to look across centuries). Modeling allows for hypothesis testing over a broad range of phenomena and helps to formulate “What if?” questions and scenarios that project future consequences of changes in ocean pH. To allow for continuous improvements in the models, modeling requires close coordination with ongoing observational activities. For example, biogeochemical models are best integrated closely with observational networks: the rapid integration of measurements into operational modeling systems will ultimately provide the basis for near-real time environmental assessments and the development of early ‘warning’ systems (e.g., detection of strong coastal upwelling events that might be detrimental to shellfish farming). In addition, models allow the estimation of unknown or unmeasured processes. Incorporating ocean acidification into biogeochemical models (a short-term goal of the Strategic Plan and end-to-end models[1] (a mid- to long-term goal of the Strategic Plan), need to be part of assessments aimed at the quantification of ecosystem and socioeconomic impacts. Models also can assist with the evaluation of impacts in the context of mitigation strategies or to help design more cost-effective monitoring strategies.

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[1] End-to-end models combine into a single modeling framework separate models representing processes across all trophic levels, from the lower end of single-celled primary producers up to top predators.

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the goals of Theme 3 are mainly expressed in terms of model development and less in terms of scientific objectives (which are the 'drivers' of model development). This limits the extent to which the modeling efforts of Theme 3 can be linked to goals found in other Themes. For example, no specific mention is made of how the improved understanding of processes and mechanisms (as part of understanding the impacts of ocean acidification) will be incorporated into improving models. Because this timely transfer of knowledge may prove difficult, the strategic plan needs to give specific consideration to how this can be facilitated, in particular when developing the implementation plan. The development and implementation of major oceanic processes (e.g., carbonate production and dissolution, nitrogen cycling, carbon assimilation) and biological processes (e.g., growth and recruitment along life stages) as a function of seawater carbonate chemistry all have clear relevance to other Themes. Thus, better integration of modeling with relevant sections in other Themes of the Strategic Plan is needed. For example, how will the monitoring activities in Theme 1 benefit from—and provide assistance to—modeling? What are the likely contributions of modeling to the evaluation of local mitigation and adaptation measures, an important issue within the socioeconomic framework of Theme 5?

Theme 3 also identifies important shortcomings in current biogeochemical models and identifies areas where model improvement is crucial in the context of impact assessments. However, it does not discuss the uncertainties inherent to model results, which would place the potential contributions and limitations of models into a more complete perspective. In addition, model development, in particular increasing model complexity, can benefit from model-data evaluation. The Strategic Plan could be improved by discussing how the use of multiple models can enhance modeling efforts. Currently, multi-model studies are the present day "best practice" in carbon cycle research (e.g., Orr et al., 2001). Steinacher et al. (2010) illustrate how the insights provided by several models can be combined to improve future projections. Multi-model projections will further allow a first appreciation of uncertainties linked to the assessment of impacts on biogeochemistry, as well as on marine resources (Stock et al., 2011).

Modeling could contribute to the FOARAM Act and specifically to the requirement to *'enhance monitoring and detection capacities,'* by developing an integrated approach combining continuous environmental data acquisition and operational modeling systems. At the scale of regional systems, this could evolve, in the long term, toward an early 'warning' system. For example, the shellfish industry would likely benefit through the development of models that allow rapid detection and short-term forecasting of strong upwelling events that bring low pH water to shallow, near-shore

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regions. Such low pH water below the surface mixed layer results from respiration of organic matter and associated CO_2 release, which can be exacerbated due to coastal eutrophication.

Some of the statements in Theme 3 appear to reflect an incomplete analysis of models used for ocean acidification and carbon cycle research. For example, our committee was surprised to see that the short term goals include a statement to *"expand implementation of alkalinity as a tracer and incorporation of PIC and remineralization formulations in BOGCMs."* Ocean-Carbon Cycle Model Intercomparison Project (OCMIP) models have already been including the carbonate cycle and several present-day state-of-the-art models also include prognostic total alkalinity and a parameterization of the marine carbonate cycle taking into account several forms of calcium carbonate (e.g., Gangsto et al., 2011).

The issues of time frame (short- versus long-term studies) and prioritization of efforts are not adequately developed in some cases. For example, the development of an integrated description of processes occurring at the land-ocean boundary is stated as a long-term objective (10 years). However, there are no intermediate steps identified over the first 3 to 5 year period toward achieving that goal. How is the coupling of land and ocean processes envisioned to occur and how should efforts to study these processes be prioritized? In particular, which modeling approaches could be proposed to tackle the diversity and complexity of coastal systems?

In summary: The introduction would benefit from a fuller description of how modeling will contribute to the objectives of the Strategic Plan. In particular, it could explain how model studies can contribute to advancing each goal outlined in the FOARAM Act. In addition, the Strategic Plan could contribute to a more effective research program if it highlighted the need for integration of model studies with other research activities, such as observation and monitoring. The Strategic Plan needs to be expanded to include a discussion about the challenges related to modeling; limitations and uncertainties of model results; and the key issues related to model skill.

THEME 4: TECHNOLOGY DEVELOPMENT AND STANDARDIZATION OF MEASUREMENTS

The FOARAM Act (page 9) mandates a Program Element to be developed with a focus on "*[t]echnology development and standardization of carbonate chemistry measurements on moorings and autonomous floats*" in the IWGOA Strategic Plan.

Theme 4 has an appropriate focus in terms of this mandate of the FOARAM Act. After a general discussion of issues related to improve-

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ments in technology and standardization of measurement protocols, this section lists a variety of *goals*—separated into short-term and long-term categories—that aim to address these concerns. Whereas these goals are in accord with the requirements for this particular Program Element of the Act, as with much of the Strategic Plan, there is not a clear statement of priorities (see Chapter 2 of this report for further discussion).

Ocean acidification research encompasses a wide variety of approaches including environmental observations and laboratory manipulations, and it requires technology for the measurement of a wide variety of parameters, both chemical and biological. Theme 4 discusses such technology and methods development, and also emphasizes the need for effective standardization of measurements. The IWGOA is to be commended for stressing so effectively the critically important need to develop standardized methods for the broad research community studying ocean acidification. The presentation in Theme 4 draws on a variety of previously published reports to emphasize two primary concerns: comparability of measurement approaches and availability of improved technology for such measurements.

Overall, the text of Theme 4 makes many good points about the need for a focused, high quality plan for ocean acidification measurements, including the need for documentation, reference materials, training, and regional centers of expertise. However, the diverse topics treated in this Theme are not pulled together in an effective way to fashion a clear strategy. We offer several explicit suggestions for improving this component of the Strategic Plan. Many of our concerns reflect similar problems found in other Themes, and are due, in part, to the limited integration across Themes in the Plan. For example, the objectives of Themes 1, 2, and 3 cannot be fulfilled due to deficiencies that need to be addressed in Theme 4. The opening paragraphs of this section would be improved by referring to priorities from other Themes that require either technological development or methods of standardization, or both. A short preface and some reorganization of content would make this a stronger section with clear links to the national ocean acidification strategy. Considering the fundamental importance of the inorganic carbon system for both the monitoring of ocean acidification and for studies of biological and ecological consequences, the Strategic Plan could benefit from a short primer for readers to review the basic concepts. More importantly, in this section the IWGOA has the opportunity to stress the fundamental dependence of high quality research on the advances in technology development.

Of great importance to this Theme are two fundamental questions: "What should be measured?" and "What is the needed accuracy/precision of these measurements?" These questions are of core relevance in any effort to address comparability of ocean acidification measurements

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across various methodologies and for guiding the improvement of technology for such measurements. The Strategic Plan lacks adequate detail on these central issues. Thus, it does not include an exhaustive list of what needs to be measured or an adequate discussion of the varying requirements for accuracy and precision in different types of contexts. Consequently, the Theme's discussions of how to improve the comparability of measurement approaches are somewhat vague.

In the context of needed levels of accuracy and precision in a given type of study, this Theme seems to provide the impression that all measurements require a state-of-the art level of uncertainty. While that degree of sophistication may be ideal, it may often be unnecessary considering the cost and training required for some measurements. Instead, a more nuanced approach could be to modulate the acceptable level of uncertainty (or error) for measurements in relation to particular research goals and funding. For example, carbonate system parameters may need to be measured with more or less accuracy and precision depending on the use of those data for hydrographic, biological, or other studies. Open ocean methods for high precision measurements of CO_2 chemistry (i.e., Dickson et al., 2007) may not be necessary for similar measures in perturbation experiments or in highly variable environments. This distinction has already been emphasized in our analysis of Theme 1.

The committee finds that integration among Themes in the Plan could be improved if recommendations from this section concerning measurement standards (and to a lesser extent technology development) were linked more clearly to Themes 1-3. Thus, measurements discussed as related to monitoring in Theme 1 would be associated with recommendations for standards for the specified measurements in Theme 4. The Strategic Plan would also benefit from a more explicit explanation of core chemical, and if possible, biological measurements or a process by which such core measurements will be identified. Discussion in Theme 4 needs to also consider the relevance of these chemical and biological measurements (especially biological) as input for ecosystem models, thereby providing a link to core issues in Theme 3.

The discussion of technology development is somewhat less complete than the discussion of the set of necessary measurements (and their precision) required for gathering ocean acidification data. The text and long-term goals identify a need for improved, autonomous CO_2 system measurement technology of various kinds, but make little concrete mention of other technology needs. The Strategic Plan notes the well-known difficulties involved in ensuring development and commercialization of new instruments, but without really providing any new insights into how to address this effectively. The Plan does mention some Federal mechanisms that are in place: NOPP (the National Oceanographic Partnership

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Program); the NOAA Alliance for Coastal Technologies (ACT); the NSF Oceanographic and Interdisciplinary Coordination Program; and the various Federal Small Business Innovation Research (SBIR) programs. However, no effort has been made to indicate how these entities could work together to achieve the goals established in this Plan. The Strategic Plan thus could be strengthened by providing a roadmap that suggests effective ways for different organizations, including Federal government programs and private industry, to work in a coordinated fashion to develop improved technologies and evolve mechanisms to make these technologies accessible to the wide community of investigators in ocean acidification research and monitoring efforts.

Theme 4 also includes two other key concepts: the establishment of Centers of (measurement) Expertise and Community Research Facilities for ocean acidification perturbation studies. Such communal facilities, properly managed and operated, could provide a substantial boost to U.S. research needs by providing expertise, laboratory facilities with state-of-the-art equipment, and training to the community of ocean acidification researchers that will be needed. As new technology is developed, centers would play an important role in introducing users to this new apparatus. An example of such a development is the evolution of free ocean CO_2 enrichment (FOCE) technology, which is being used to investigate ocean acidification in a variety of marine habitats, including coral reefs and kelp forests. It would be useful to more thoroughly specify how many of these facilities are required (including, perhaps, a broad regional distribution) and to indicate how they could be funded and managed to benefit the U.S. ocean acidification research community. The role of these Centers in integrating U.S. ocean acidification research and monitoring with other parallel international efforts needs to be emphasized as well. Issues of standardization, comparability, and quality of data are of critical relevance in global scale research as well as within the U.S. ocean acidification program.

*In summar*y: To make Theme 4 of the Strategic Plan a more effective vehicle for communicating the Theme's goals and how and by whom they will be implemented, more detail is needed. In the committee's view, principal gaps in this Theme include issues of specific goals of measurements (What is to be measured—and why?—and with what accuracy?); priorities (Which goals are most important and which are of secondary significance?); and costs (What are the likely costs, and how can the goals be met with the available funds through appropriate prioritization efforts and cooperation among agencies and international entities?). This third concern is particularly important when considering the role that different federal agencies might play in ensuring that the various goals will be met.

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An additional concern relates to the need for a stronger emphasis in the Strategic Plan on development of new technologies for chemical and biological monitoring efforts. We have pointed out the significance of development of in situ sensors for monitoring ocean chemistry over space, time and depth. Needs for effective in situ detectors for tracking biological changes also exist; development of this technology lags well behind development of chemical sensors. As in the case of chemical sensors, development of effective in situ instrumentation for biological monitoring could benefit from collaborations between researchers in academic and governmental programs and engineering partners in industry. Improved technology for biological studies also may be required for mechanistic physiological experimentation. For example, new tools and techniques may be needed for measuring changes in pH at the systemic, cellular, and subcellular levels in marine species that require instrumentation not available off the shelf from manufacturers of biomedical equipment. Finally, in common with many of the other Themes in the Strategic Plan, there is little mention of appropriate metrics for evaluating progress (see Chapter 2 of this report for detailed discussion).

THEME 5: ASSESSMENT OF SOCIOECONOMIC IMPACTS AND DEVELOPMENT OF STRATEGIES TO CONSERVE MARINE ORGANISMS AND ECOSYSTEMS

In recognition that the effects of ocean acidification may include profound influences on human society as well as on marine ecosystems, the FOARAM Act specifies in its list of Program Elements that an "*[a]ssessment of socioeconomic impacts of ocean acidification and development of adaptation and mitigation strategies to conserve marine organisms and marine ecosystems*" be undertaken. This summary statement concisely expresses the socioeconomic requirements given in the FOARAM Act: "*The purposes of this Act are to provide for . . . (3) assessment and consideration of regional and national ecosystem and socioeconomic impacts of increased ocean acidification; and (4) research on adaptation strategies and techniques for effectively conserving marine ecosystems as they cope with increased ocean acidification.* In Section 6 of the Act, it is further stated that the NOAA Secretary may adopt a plan that supports "*critical research projects that explore the effects of ocean acidification on ecosystems and the socioeconomic impacts of increased ocean acidification that are relevant to the goals and priorities of the strategic research plan.*"

These socioeconomic issues are especially challenging in view of several factors, notably (1) the difficulties in extrapolating from often poorly understood ecological changes to impacts on human populations and their economies, (2) uncertainties about optimal adaptation strategies to buffer society against effects of ocean acidification, and (3) the complex

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environmental changes in the ocean and the political and economic realities that such efforts would encounter.

The introduction to this Theme is well written and, in keeping with the FOARAM mandate, this section rightly highlights the linkages between increasing acidification and potential impacts on the provision of ecosystem goods and services that include, for example, fisheries production, recreation, and conservation of marine organisms and ecosystems. The introduction also correctly points out the importance of recognizing the projected rate of changes in ocean chemistry, and the potential severity of the socioeconomic impacts that might result as a consequence. However, the introduction makes very little reference to the need to develop "*adaptation and mitigation strategies to conserve marine organisms and marine ecosystems*" as specified in the FOARAM Act. The introduction would also benefit from discussing how ocean acidification takes place in the context of other human induced changes in the ocean, such as climate change, overfishing, and marine pollution.

The committee also supports the idea presented in this Theme that socioeconomic outcomes are one possible method of prioritizing the natural science research on ocean acidification (e.g., by emphasizing research on the impacts on commercially important species or species listed under the Endangered Species Act). The discussion, however, could be strengthened by providing an example of the process that could be used for priority setting, such as a 'value of information' study (e.g., Costello et al., 1998).

The issue of prioritization also arises in another critical context, where the committee believes re-evaluation and improvements of the Strategic Plan are warranted. In the introduction to Theme 5, it is stated that, *"[t]o some extent, socioeconomic research must follow research in the natural sciences."* For the reasons discussed below, we find this statement to be incorrect or at the very least potentially misleading. The statement can potentially be misconstrued to mean that initiating socioeconomic research at this time is not necessary or less urgent. The committee disagrees with such an interpretation because investments in long-term data collection and studies that will be used in measuring impacts need to begin now. Specifically, to improve modeling, impact, and adaptation studies in the future, social scientists need to be incentivized to develop time series and data networks that can then link the natural sciences questions with the social and economic sciences questions. This presents another rationale for strong integration across Themes 3, 5, and 7. The committee believes that it would be unwise to wait for impacts to happen, or for the probability of them occurring to reach some threshold, before starting this research. For example, the U.S. could currently be increasing its investments in socioeconomic research to assess the benefits to the nation from ocean

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recreational activities and conservation of marine species. In addition, studies on the demand and supply of shellfish and other commercially harvested species are needed. Such research would provide valuable insights regardless of the magnitude or timing of the ocean acidification impacts on those resources.

The introduction to this Theme does not mention the importance of social science (e.g., political science, economics, anthropology) and interdisciplinary research (e.g., conservation biology, sustainability science) in the development and evaluation of management strategies (e.g., policies, regulations) to meet National Ocean Policy objectives. In other words, the focus of the section is centered on quantifying socioeconomic impacts rather than on the design of institutions and regulations that facilitate adaptation to ocean acidification (e.g., Kling and Sanchirico, 2009; Sanchirico, 2009), on the potential for technology solutions, and on conservation strategies more broadly. Ocean acidification at the global scale can only be mitigated through policies that address lowering CO_2 emissions. Given the well-known difficulties in finding policy options to lower CO_2 emissions, the committee limits its review and discussion under this theme to research related to impacts, adaptation, and conservation.

A focus on adaptation is critical for ensuring that well-informed analyses are carried out to create policies that are effective in coping with the effects of acidification. There is a possibility that current governance and regulatory environments may provide incentives that lead to maladaptive responses, such as is the case with disaster relief packages or other subsidies that maintain overcapacity in commercial fisheries. Another example is the regulatory structure around fishery management that creates incentives for fishermen to specialize in certain species (e.g., purchasing of specific gear and construction of processing facilities), when in fact we might want to think about developing incentives to create a nimble fishing industry that can respond to the coming changes as a means to lessen potential damages. In the development of programs for adapting to acidification, it will be important to take an interdisciplinary approach that incorporates insights from marine conservation and conservation biology more generally and considers the role of other environmental stressors. Such an integrated analysis could provide an important link to Theme 2 (e.g., under "*Food Webs and Ecosystems*").

Furthermore, the social sciences could provide valuable information on not only the economic, ecological, and social benefits and costs of ocean acidification, but also the risks of different mitigation techniques. There are multiple geo-engineering methods being considered, but presently they do not offer an adaptive response to ocean acidification (Matthews et al., 2009). That is, geo-engineering strategies commonly focus only on reducing global warming and fail to take acidification into account. The

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only mitigation techniques discussed in this section of the Strategic Plan are reductions in greenhouse gas emissions and policies that improve the overall health of ecosystems by reducing other stressors (e.g., reduction in fishing catch, habitat restoration, and improvement in water quality).

Since the draft of the Strategic Plan was written, relevant additional studies have appeared that begin to estimate socioeconomic impacts of ocean acidification, for example, by estimating impacts on industries such as global shellfish production (Narita et al., 2012) and the U.S. mollusk fishery (Moore, 2011). Both of these studies highlight the need for additional socioeconomic research on the economics of shellfish demand and production under changing ocean conditions. For example, Narita et al. (2012) discuss the importance of measuring the economic impacts on consumers and producers that might occur if rising income levels in China and elsewhere lead to an increase in demand for shellfish.

While it is true that the number of socioeconomic studies on the impacts of ocean acidification is limited, the Strategic Plan could mention the existing social science and interdisciplinary literature more completely and allude to research frontiers and relevant evolving programs. For example, the National Science Foundation is funding a considerable amount of research on decision-making under uncertainty, which has relevance for developing mitigation and adaptation strategies given the uncertain future outcomes of ocean acidification. Another related body of literature is the work in marine ecology, marine conservation, and economics on measuring the ecological and socioeconomic impacts of marine reserves (e.g., Fox et al., 2012 and citations therein), which represent one potentially important conservation tool in the ocean acidification adaptation toolbox.

Whereas the goals presented in Theme 5 are consistent with the FOARAM Act, their wording does not easily translate into measurable metrics that could be used to assess the progress of the forthcoming implementation plan (e.g., the use of verbs such as 'support', 'encourage', and 'foster'). In addition, the way the goals are ordered (short- vs. long-term) is inconsistent with how rigorous research on decision-support tools is undertaken (e.g., Levin et al., 2009). As the Strategic Plan currently states, scoping discussions with stakeholders and decision-makers (e.g., to understand what questions the integrated models need to address) are long-term goals, while the development of integrated models that will be used in decision-support tools is a short-term goal. Without engaging stakeholders and decision makers in the scoping study, however, there is no guarantee that the integrated models will be useful in a decision-support context. Therefore, reordering the goals in terms of short-term and long-term efforts is needed.

Several other components of the analysis presented in Theme 5

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require clarification, expansion, and/or correction. We briefly discuss these below and offer suggestions for improving the manners in which these issues are discussed.

Stakeholder groups. Key to the success of socioeconomic efforts tied to ocean acidification is identification of, and then, effective interactions with the relevant stakeholder groups. This issue is brought up in Theme 5, but requires further development. The subsection on identifying stakeholder groups needs to be explicitly tied to the National Program Office and the actions described in Theme 6.

Mitigation. The section highlights how gross domestic product (GDP) is a useful summary statistic of economic impacts. That is correct for market goods and services, but GDP is woefully inadequate for measuring the totality of ocean acidification impacts given that many of them occur outside of markets (e.g., conservation of marine species). If Theme 5 is to have this discussion, it needs to be expanded to discuss the role of green accounting, which factors environmental costs into the overall financial consequences of economic activities (e.g., Boyd and Banzhaf, 2007).

The subsection on mitigation also needs to discuss how Marine Protected Areas (MPAs) and Long Term Ecological Research (LTER) programs can be used to measure the socioeconomic and ecosystem impacts of ocean acidification, and if there is a potential to use information from MPAs and LTERs in the development of strategies. The discussion of mitigation also ought to consider the potential for research around the socioeconomic and ecological costs and benefits of geo-engineering.

Human Adaptation. The discussion could be enhanced by a set of socioeconomic research questions that need to be addressed. For instance, as discussed above, there is a need to undertake research to understand whether the current regulatory frameworks are creating incentives for maladaptive behavior. To help readers understand the breadth of important research that is needed on developing adaptation strategies, additional examples beyond hatchery operations would be valuable (e.g., conservation of marine species).

In summary: A reaffirmation about the interdependence and the timeframes of basic natural science and social science and interdisciplinary research is needed. An explicit statement in the Strategic Plan is needed that explains that social science research should not be delayed until natural science research has brought problems into focus. Social science research, informed by natural science, can help the nation to better prepare for the effects of ocean acidification. Furthermore, as emphasized above, prioritization of the program's natural science goals can be informed by societal and socioeconomic research needs. The social science research agenda on ocean acidification needs to be expanded to highlight

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the important and critical roles of this research for not only measuring impacts but also for assessing mitigation and adaptation policies and regulations. The contributions of research in associated disciplines (for example, conservation biology and decision making in the face of uncertainty) need to be incorporated into the broader analysis given in this Theme.

THEME 6: EDUCATION, OUTREACH, AND ENGAGEMENT STRATEGY ON OCEAN ACIDIFICATION

Theme 6 is one of two additions (along with Theme 7) that the IWGOA made to the five Program Elements given in the FOARAM Act. However, even though the FOARAM Act did not include an explicit Program Element focused on the issues treated in Theme 6, the Act does state on pages 3 and 4 that there is a need to "*facilitate communication and outreach opportunities with nongovernmental organizations and members of the stakeholder community with interests in marine resources.*" The committee views this requirement as an important component of a National Ocean Acidification program for several reasons. As stated on page 6 of the Strategic Plan, the two additional Themes are "*inherent to the successful implementation of the plan*," (i.e., they are critical to attaining the FOARAM-mandated objectives of the first 5 Themes). On page 47 of the Strategic Plan, the need for Theme 6 is stated as follows: "*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*."

Overall, the committee believes that the analysis given in Theme 6 does an excellent job of emphasizing what needs to be done in "*education, outreach, and engagement strategy*" in the face of the challenges in communicating science to a broad public audience. The existing players in education and outreach are listed (but with a few key omissions; see below) and a strategy is outlined for identifying important new linkages and collaborations, both nationally and internationally. The development of programs will be iterative and monitored over time and will involve a pivotal role for the National Program Office (see below). Therefore, attaining the goals of Theme 6 seems possible if adequate funding is available. It will be important to engage the social scientists as part of implementing the education and outreach component. Here, private foundation support might be crucial for supplementing governmental funding.

The development of Theme 6 strikes the committee as having a good balance between a presentation of basic strategies, which is the key role of the Strategic Plan, and offering suggestions for specific implementations. This is a difficult balance to achieve, but this section of the Strategic Plan

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has done a commendable job of presenting some concrete implementation materials as well as outlining a good complement of basic strategies.

The challenges in reaching the goals of Theme 6 are succinctly summarized in the Strategic Plan,[3] where it is emphasized that, ". . . *interest in, and appreciation for, science in the United States is extremely low.*" Much of the remainder of the discussion in Theme 6 outlines strategies for overcoming the challenges inherent in effectively communicating a topic that the public will almost certainly find difficult to understand. Unlike the changes in temperature, shifts in rainfall patterns/intensities, and increasing storm intensity that may accompany global change, decreases in oceanic pH are difficult to see or feel directly. Moreover, discussions of acidity that appropriately utilize the pH scale preferred by marine chemists are apt to befuddle a lay audience. Thus, the challenges in educating and involving the broader public in ocean acidification-related issues and activities are substantial. One approach for catching the broader community's attention may be to familiarize the public, as well as Congress and relevant federal and state agencies, with the socioeconomic consequences of ocean acidification (see Theme 5). This type of education could allow the effects of ocean acidification to be appreciated as having immediate human relevance, including economic consequences.

The National Ocean Acidification Program via the National Program Office is slated to play a major role in addressing the tasks described in Theme 6. It seems beneficial to develop and integrate education and outreach effort at the Program level to reduce redundancy and to engage education professionals and social scientists. The Program Office can serve as a centralized clearing house for communication in the arena of education and outreach, and serve as a principal point of contact for up-to-date, scientifically valid information. For example, a centralized web portal managed by the Program Office is proposed.[4] This asset could be of broad importance in education/outreach efforts and serve as a credible source of information for anyone interested in ocean acidification. It could be an especially effective vehicle for providing educational content and for evaluating the success of different educational and outreach efforts (e.g., by including a "What works and what does not work?" type of blog, where educators, journalists, and others could share experiences or ideas). Ongoing evaluation of the education and outreach programs will be critical for ensuring that they provide materials that are accurate, up-to-date, and accessible to a wide spectrum of audiences with diverse backgrounds, and that they take advantage of the evolving manners in which information is exchanged (e.g., via social media). Lastly, a centralized web portal

[3] IWGOA, pg. 47.
[4] IWGOA, pg. 48-49.

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should include links to other scientifically credible websites that present the science of ocean acidification and global change science more broadly.

The committee believes it is appropriate to include in the Strategic Plan (within Theme 6) a brief discussion regarding the attention that needs to be given by educators to the way in which CO_2-induced changes in acidity are discussed. Use of the terms *acid* and *acidity* in discussions of ocean acidification can be misleading. Except in cases such as natural CO_2 vents like those near Ischia, Italy, the entry of CO_2 into the ocean does not actually make the ocean acidic in the sense used by chemists. It will be necessary—but truly challenging—to familiarize the public with the pH scale for expressing how a change in the amount (concentration) of the acidifying factor in question, the hydrogen ion (proton; H^+), is affected by adding CO_2 to seawater.

One important omission exists in Theme 6: Communicating information to news/wire services (U.S. and international) is not discussed. This is one important way of getting the word out to a broad audience, and the National Program Office's web portal could play a key role in this endeavor. The committee suggests that this omission be addressed by the Strategic Plan, to ensure that information on ocean acidification is communicated in as broad and an effective way as possible.

Coordination and integration with other existing education/outreach programs is a central focus of Theme 6. This is an important goal, in view of the variety of target audiences and the diversity of governmental and nongovernmental entities that will be involved in communicating ocean acidification issues in both the U.S. and abroad. Box 10 in the Strategic Plan, which provides a list of "programs and organizations with existing education and outreach initiatives," represents a helpful and extensive list of programs and organizations involved in global change issues, including ocean acidification. The committee believes a major omission from this particular list is the effort being made by public aquariums, museums, and zoos to provide high quality, publically accessible environmental education. For example, U.S. zoos and aquaria receive over 175 million visitors annually, and the Association of Zoos and Aquariums reports that 94% of those visitors feel that such organizations teach children about how people can protect animals and the habitats they depend on (AZA website, 10/2012). They have already been coordinating efforts on climate change education.[5] These outreach efforts need to be recognized and the National Ocean Acidification Program could approach this climate change collaboration for its outreach effort. The Strategic Plan's section on *Engaging Stakeholders* or *Linking to Existing Programs and Organizations*

[5] http://www.aza.org/Climate-Change-Education-Initiatives/.

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could be updated with a reference to the EPOCA Reference User Group[6] and the California Current Acidification Network.[7] These two programs could serve as models and ways to leverage efforts within the National Ocean Acidification Program.

Theme 6 emphasizes the international nature of education and outreach, and the proposed efforts therein to develop international collaborations all seem reasonable, although lacking in detail. Box 10 lists eight international programs (along with supporting scientific organizations and NGOs) with potential to make strong contributions in this arena. Public aquaria, museums, and zoos in other nations would be appropriate additions to consider as potential international partnering organizations.

Whatever the partnering organizations happen to be—and the Strategic Plan indicates that this will be an evolving group whose numbers and responsibilities will change as needs for ocean acidification education and outreach change—the fact that the proposed National Program Office will coordinate collaboration efforts is an important aspect of the Plan. This sort of centralized coordination and communication will work against redundancy and help the various participants in the United States and abroad learn from one another. An important aspect of outreach and education is to ensure knowledge transfer to the applied arena where policy issues related to mitigation and adaptation are developed. A centralized and highly credible source of information is likely to be extremely valuable in this context.

In summary: The committee commends the IWGOA for adding education and outreach as a separate Theme of the Strategic Plan and for presenting a well-balanced discussion of the needs and goals for ocean acidification education. The committee noted two omissions that merit attention: A discussion of (1) outreach efforts to the news media and (2) ways to engage public aquaria, museums, and zoos, which enjoy a high level of credibility with the public and could be a major asset in ocean acidification education and outreach.

THEME 7: DATA MANAGEMENT AND INTEGRATION

Although "Data Management and Integration" is not a specific Program Element in the FOARAM Act, the Act states that a Joint Subcommittee on Ocean Science and Technology (JSOST) [now SOST] of the National Science and Technology Council (NSTC) shall coordinate Federal activities on ocean acidification. One of SOST's duties is to "*establish or*

[6] http://www.epoca-project.eu/index.php/what-do-we-do/outreach/rug.html.
[7] http://c-can.msi.ucsb.edu.

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designate an Ocean Acidification Information Exchange to make information on ocean acidification that is developed through or used by the interagency ocean acidification program accessible through electronic means, including information that would be useful to policymakers, researchers, and other stakeholders in mitigating or adapting to the impacts of ocean acidification." Thus, SOST is tasked with developing a strategic plan for federal research and monitoring on ocean acidification that will provide, among other things, a description of planned data collection and database development activities. IWGOA is to be commended for adding this Theme to the Strategic Plan, as it treats a number of critical functions.

The Plan addresses the main requirements of the above legislation with a breadth of coverage that is quite comprehensive. Key topics such as data access frameworks, web portals, availability of data, sensor information, metadata and archival data are all addressed. However, while the general scope is appropriate, there is insufficient detail in addressing some of the important elements associated with the FOARAM Act's mandate. We discuss these limitations and offer suggestions for strengthening the Strategic Plan below.

The committee finds that Theme 7 does not explicitly address what information or data will be made available to policymakers and other stakeholders, in addition to the traditional data archives used by researchers. The FOARAM Act requests an "*information exchange*," not just a data archive. Creative procedures will need to be developed for extracting and sharing data once it is compiled.

Nothing in the FOARAM Act defines the explicit roles of NOAA, NSF or NASA in contributing to the tasks related to data management and integration; the Strategic Plan also does not address this issue. Considering the likely difficulty in integrating agency activities, attention to clarifying these roles is needed. A successful ocean acidification research program will require a data delivery system that allows everyone access to sufficient metadata to enable accurate integration of disparate data and essential documentation.

Much of Theme 7 addresses archiving of traditional physical and chemical environmental data, an activity that the scientific community is familiar with. However, the National Ocean Acidification Program will be addressing the effects of ocean acidification on biology, chemistry, and socioeconomic issues; thus, datasets will need to be included and made available from disparate research on, for example, animal behavior, mechanisms and rates of natural processes, and human impacts and responses. Natural science studies may involve monitoring efforts of natural systems or data gathering from perturbation experiments. Experimental manipulation experiments may be performed in the laboratory, in mesocosms, or in the field. Results may involve experimental data as well as modeling

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activities. Similar considerations apply to data gathered in socioeconomic studies. Currently, methods for archiving and serving these diverse types of data are not well developed in the Strategic Plan, nor is a process outlined for developing such methods. The Strategic Plan would benefit from outlining a process that can address these questions of methodology and that would bring together natural and social scientists regularly to confer about scale and time frames for data collection and data management.

Consistent definitions for measurement variables are needed. Many variables are measured in perturbation experiments, and data are generated for parameters and processes from the molecular scale to the mesocosm scale. In particular, management of molecular data is not addressed in the Strategic Plan, yet the amount of information generated is huge. Many databases already exist (e.g., http://www.ebi.ac.uk/panda/Publications/mbd1.html), but unambiguous definitions of many other ocean acidification variables are necessary. It might be beneficial and more efficient to embed ocean acidification data management within an existing data management activity. Whether and how the data management is developed requires additional detail in the Strategic Plan. In any case, the curators of the data collection should work in close collaboration with members of the scientific research community in identifying, adopting and/or developing the requisite data management policies and procedures. This coordination is needed across the different Federal agencies involved in the U.S. ocean acidification program, e.g., NOAA, NASA, and the NSF, and with international entities (see below).

The Plan rightly highlights the fact that metadata needs must be identified early on. Work has started along these lines as part of a recent, multi-agency initiative (Newton, 2012), and an associated report on data management has been issued (CIMOAD, 2012). Although the Plan discusses data archiving and metadata collection, it leaves out a third and extremely important part of the data management triad: the *uncertainty* of the data. Methods for archiving and accessing uncertainty estimates associated with the data are needed, not simply a statement of analytical error.

Pivotal to the success of a program for effective archiving and distribution of data is the timely availability of data. This critical issue is not adequately addressed in the Plan. Major efforts have been made to compile published data on biological responses to ocean acidification (e.g., Nisumaa et al., 2010), and such compilations have proven to be a valuable tool for meta-analyses (Kroeker et al., 2010; Liu et al., 2010). However, key data sets are missing from this compilation, despite recovery efforts by program managers.

In summary: Examples of the different types of ocean acidification-related data sets to be managed and integrated need to be stated explicitly in

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Theme 7. The goal to address the requirements and inherent challenges for managing diverse types of data sets needs to be added. New and creative procedures will most likely be needed for handling and disseminating these forms of data. In addition, the Strategic Plan needs to indicate how uncertainty estimates will be incorporated, both in the extracted information as well as in the archived data. The importance of understanding and reporting data uncertainty is compounded when generating synthesis products (as described previously in Theme 2). The Strategic Plan could be improved by pointing out the need for a mechanism by which explicit, strict requirements for data deposition will be developed and enforced, to ensure that data sets are made available to the broader ocean acidification community in a timely manner. Any new ocean acidification research program needs to strictly enforce rules concerning data submission. Because of the broad international effort to study ocean acidification, programs for data archiving, management and distribution need to be as consistent as possible across international boundaries. This is essential for ensuring that data sets are utilized in an optimal manner, notably in the types of meta-analyses in natural science and socioeconomic analyses that are certain to be of growing importance in the future. Lastly, contributing to international efforts that facilitate effective and consistent mechanisms for archiving and distribution of ocean acidification data would be an important goal to add to the Strategic Plan. International efforts, like national efforts, need to work to make ocean acidification data publicly accessible even prior to publication.

IN CONCLUSION

The committee concludes its analysis of the IWGOA Strategic Plan for Federal Research and Monitoring of Ocean Acidification by reiterating our judgment that the Plan has done a generally excellent job of addressing the several Program Elements in the FOARAM Act that serve as the principal mandates for developing a comprehensive National Program on Ocean Acidification. The committee intends to offer helpful suggestions that will lead to improvements of the Strategic Plan and, thereby, to a more effective National Program for addressing the numerous issues contained under the wide umbrella of ocean acidification.

Because these issues span such a broad range of phenomena, including the inorganic chemistry of seawater, diverse types of biological effects, and potentially large socioeconomic consequences that will require effective adaptation, the National Program meets a critical need for facilitating the integration among the separate disciplines of the natural and the social sciences required to study ocean acidification. Integration among different fields of study will allow appropriate transfers of knowledge

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across disciplines and help ensure that the discoveries of the natural sciences (chemistry, oceanography and biology) will serve the needs of social scientists who address the economic consequences of acidification and the policy makers who will be instrumental in funding programs in mitigation and adaptation. Conversely, social scientists' needs for key types of information to allow effective research and policy formulation should inform and guide, as appropriate, efforts in the natural sciences. Communication and integration among disciplines therefore are key to the success of the National Program.

Throughout the many types of scientific efforts needed for effective and comprehensive study of ocean acidification, there is a common need for informed prioritization of what is to be done. Criteria need to be established for prioritizing different lines of studies, and decisions on priorities should be done in a continuing and iterative manner, based on degree of success of ongoing programs and the discovery of new information that may reshape the program's priorities. Consequently, a common need exists in all lines of investigation of ocean acidification for metrics to evaluate a program's success. The need for metrics is, in fact, inseparable from the need for continued reexamination of priorities among different programs of study and readjustment of priorities as new insights are obtained.

Finally, as stressed throughout our analysis of the Strategic Plan, the scope of the National Program in Ocean Acidification necessitates the establishment of a National Program Office. There is urgency in developing a mechanism for establishing this Office, so that it can be functional from the very start of the National Program. Key decisions that are likely to influence the focus and long-term success of the Program will be made in the earliest stages of planning. Thus, among the several critical roles of the National Program Office is the development of strategies for implementing the efforts that will be required to achieve the goals presented in the Strategic Plan. Implementation will require many decisions on (1) the types of research to be pursued (prioritization), (2) how these different research endeavors can best be achieved through efforts of the different collaborating agencies of the Program (coordination), and (3) how successfully research activities are reaching the Strategic Plan's goals (metrics for evaluation). The need for effective and cost-efficient cross-disciplinary coordination of research efforts requires a central Program Office that can facilitate interagency cooperation and maintain an ongoing exchange of information that allows the results of the diverse research efforts to be most effectively communicated among different national and international groups studying ocean acidification. A National Program Office can also help to facilitate the distribution of information to Congress and to the public at large. In a limited funding environment it will be essential to

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inform Congress in a convincing manner of the need for broad studies of ocean acidification. Support by the public will be essential for this effort. Thus, the inclusion in the Strategic Plan of a strong program for education and outreach is wise. Through these wide-ranging activities, the National Program Office can help to implement a powerful and integrated scientific program on ocean acidification and assist in the transfer of information and technology from the program's research and monitoring efforts to the groups that will be responsible for developing effective programs for enabling society to adapt to the as yet largely unknown consequences of ocean acidification.

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APPENDIX A

Statement of Task

An ad hoc National Research Council committee will review the Interagency Working Group on Ocean Acidification (IWGOA) strategic plan for federal research and monitoring on ocean acidification based on the program elements described in the FOARAM Act of 2009 and the advice provided to the IWGOA through the 2010 NRC report *Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean.*

Specifically, the review will consider the following elements:

(1) goals and objectives;
(2) metrics for evaluation;
(3) mechanisms for coordination, integration, and evaluation;
(4) means to transition research and observational elements to operational status;
(5) coordination with existing and developing national and international programs; and
(6) community input and external review.

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APPENDIX B

Committee and Staff Biographies

COMMITTEE

George Somero, *Chair,* the Associate Director of Stanford University's Hopkins Marine Station in Pacific Grove, California and the David and Lucile Packard Professor of Marine Science, is a physiologist who examines the mechanisms that marine organisms use to adapt to their environments. Because he was raised in the far northern corner of Minnesota, it was natural for him to move to McMurdo Station, Antarctica, to conduct his Ph.D. research while a graduate student at Stanford. In Antarctica, he determined the physiological and biochemical mechanisms that enable cold-adapted Antarctic fish to carry out their physiological activities in near-freezing temperatures (–1.9°C). Somero is fascinated by organisms' abilities to cope with extremes of environmental stress and during his 42 years as a university professor, his research group has studied organisms' responses to extremes of temperature, salinity, oxygen availability, and hydrostatic pressure. This research has been done in environments as different as deep-sea hot springs, tropical seas, the polar oceans and the temperate rocky intertidal zone. Following his doctoral work, Somero did postdoctoral studies at the University of British Columbia with Dr. Peter Hochachka. Together, over a period of almost 25 years, they published three volumes on the topic of biochemical adaptation. Following his postdoctoral studies, Somero served on the faculty of the Scripps Institution of Oceanography, University of California San Diego for 21 years. He then joined the faculty of Oregon State University for four years prior to his return to Stanford and Hopkins Marine Station in 1995. His laboratory currently is exploiting many of the new molecular biological tools

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developed in biomedical research to examine the environmental biology and evolution of marine organisms. Their work not only examines basic evolutionary mechanisms of adaptation to the environment, but also supplies a foundation for predicting the effects of global climate change on marine ecosystems. Professor Somero received a Guggenheim Fellowship and is a member of the National Academy of Sciences and a fellow of the American Association for the Advancement of Science.

James Barry, with a background in biological oceanography and marine ecology, is a Senior Scientist at the Monterey Bay Aquarium Research Institute (MBARI). Jim's research program focuses on the effects of climate-related changes in ocean conditions, including ocean warming, acidification, and hypoxia, on the physiology and ecology of marine life. Other areas of expertise and research include deep-sea biology, the ecology of chemosynthetic biological communities, polar marine ecology, and the biology of submarine canyon communities. In addition to publishing over 100 scientific papers, Dr. Barry has helped inform policy-makers on ocean acidification, ocean carbon sequestration, and climate change by speaking at congressional hearings, briefings, and meetings with members of Congress. He was a contributing author to the IPCC report on climate change in the oceans, and is an author of the National Academies of Sciences report on Ocean Acidification, a National Strategy to Meet the Challenges of a Changing Ocean.

Andrew Dickson is professor of marine chemistry at the Scripps Institution of Oceanography of the University of California, San Diego. His research interests include ocean acidification, quality control of oceanic carbon dioxide measurements, biogeochemistry of the upper ocean, marine inorganic chemistry, thermodynamics of electrolyte solutions at high temperatures and pressures, and analytical chemistry of carbon dioxide in seawater. Dickson previously served on the NRC Committee on Oceanic Carbon and was the chair of the NRC Committee on Reference Materials for Ocean Science.

Jean-Pierre Gattuso is a biological oceanographer interested in the response of marine organisms to global environmental changes, including ocean acidification. His research has focused on the response of pelagic calcifying phytoplankton, but he has also done research on other calcifiers including corals and coralline algae. He is also interested in carbon and carbonate cycling in coastal ecosystems, including estuaries and the contribution of the microbial loop in the carbon cycling of pelagic systems. He is currently the coordinator of the European Project on Ocean Acidification (EPOCA) and committee member on numerous other international ocean acidification programs. Additionally, Dr. Gattuso is the founding

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editor-in-chief (with J. Kesselmeier) of Biogeosciences, an innovative journal launched in 2004 by the European Geosciences Union (EGU). He received his Ph.D. in 1987 in Biological Oceanography from the University of Aix-Marseille II, France.

Marion Gehlen is a senior scientist at LSCE (Laboratoire des Sciences du Climat et de l'Environnement). Her research interests include the evolution of marine biogeochemical cycles and ecosystems in response to climate change and ocean acidification, the biogeochemistry of marine carbonates, the contribution of coastal marine sediments to the global marine carbon cycle. Marion was a lead scientist in a major EU funded large-scale projects targeting the marine carbon cycle (CarboOcean, CarboChange) and ocean acidification (EPOCA). She is a member of the GODAE task team in 'Marine Ecosystem Prediction.'

Joanie Kleypas is a Scientist III at the National Center for Atmospheric Research. Dr. Kleypas earned a Ph.D. in tropical marine studies from James Cook University, Australia in 1991. Her research focuses on how coral reefs and other marine ecosystems are affected by environmental changes associated with global climate change. Dr. Kleypas has presented several testimonies and briefings to various subcommittees of the U.S. Senate and House of Representatives on how increases in sea surface temperature and ocean acidification affect marine ecosystems. She has led several scientific workshops on ocean acidification, and served as founding co-chair of the Ocean Carbon and Biogeochemistry Program's Subcommittee on Ocean Acidification. Dr. Kleypas was an essential member of the previous, related study on ocean acidification: *A National Strategy to Meet the Challenges of a Changing Ocean.*

Chris Langdon is a biological oceanographer and professor in marine biology and fisheries at the Rosenstiel School of Marine and Atmospheric Science, University of Miami in Miami, Florida. He received his Ph.D. in biological oceanography from the University of Rhode Island. Dr. Langdon's research focuses on coral and algae primary production, respiration and calcification, and the response of corals and coral reefs to global change and ocean acidification. He is the author of twenty-three journal articles and book chapters on the subject of corals and ocean acidification. He was a member of the Ocean Carbon Biogeochemical Program Ocean Acidification Committee for three years before rotating off in 2011. He was co-organizer of Workshop on the Impacts of Increasing Atmospheric CO_2 on Coral Reefs and Other Marine Calcifers, St. Petersburg, FL Apr. 18-20, 2005 and the OCB Scoping workshop on ocean acidification, San Diego, CA, Nov. 13-15, 2007. He is co-founder of the South Florida Coral Reef & Climate Change Lab. Langdon pioneered the use of mesocosms

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and an experimental approach to study the impact of ocean acidification on coral reefs at Columbia University's Biosphere 2 Center in Tucson, AZ. Langdon was also a reviewer for the NRC report Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean.

Cindy Lee received her Ph.D. in chemical oceanography in 1975 from the Scripps Institution of Oceanography at the University of California in San Diego and then spent 11 years at the Woods Hole Oceanographic Institution. She has been on the faculty of Stony Brook University's Marine Sciences Research Center since 1986. She has participated in many national and international research programs and has sailed all the Seven Seas. Her research is concerned with the distribution and behavior of biogenic organic compounds in the marine environment, and the role of these compounds in the global carbon cycle. Understanding how organic compounds behave requires knowledge of the biological, geological, and physical processes in the sea. Dr. Lee is interested in organic compounds in all environments, particularly seawater, surface microlayer and sediments of open ocean and coastal areas. She has been a member of the NAS Ocean Studies Board, as well as the Committee on Reference Materials for Ocean Science.

Edward L. Miles has been a pioneer and innovator in the evaluation and design of environmental policy. His research was instrumental to the development of the United Nations Convention on the Law of the Sea, a convention designed to restructure and significantly expand the legal regime for the world's oceans. He is also a key leader in the study of policies for climate change assessments. Edward Miles serves on the faculty of the Evans School and the School of Marine Affairs in the University of Washington's College of Ocean and Fishery Sciences. He teaches international science and technology policy and marine policy. Miles' research focuses primarily on problems of international science and technology policy, management of world fisheries, nuclear waste disposal, the law of the sea, comparative national marine policy, and global climate change. He has been a Ford Foundation Fellow; a Council on Foreign Relations International Affairs Fellow; a James P. Warburg Fellow at the Center for International Affairs, Harvard University; and a Senior Fellow at the Woods Hole Oceanographic Institution. He is currently a senior fellow at the Joint Institute for the Study of the Atmosphere and Oceans (JISAO), Virginia and Prentice M. Bloedel Professor of Marine Studies and Public Affairs, and co-director of the Center for Science in the Earth System (CSES). Miles previously served as chairman of the Ocean Policy Committee, National Research Council; joint appointee and chief negotiator for the Micronesian Maritime Authority, Federated States of Micronesia; chairman of the Advisory Group on the International Implications

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His main research interests include the economic analysis of policy design and implementation for marine and terrestrial species conservation, the development of economic-ecological models for forecasting the effects of resource management policies on the economics and ecology, and the control and prevention of invasive species. Twice his research has been honored with Quality of Research Discovery awards from the Agricultural and Applied Economics Association, and he was part of the team of researchers at Resources for the Future honored with FEEM's 20th Anniversary Prize in Environmental Economics. He communicates his research in economic and natural science peer-reviewed journals, including Science, U.S. Proceedings of the National Academies of Science, Conservation Letters, Marine Policy, and the Journal of Environmental Economics and Management. His research has been covered in the Wall Street Journal, Science News, National Public Radio Science Fridays, The Economist, Providence Journal, and Greenwire News Service. In addition to serving on NOAA's Science Advisory Board, he is a member of the Science Advisory committee of the Marine Ecosystem Services program at Forest Trends, on the editorial boards of Ecology Letters and Journal of Theoretical Ecology, and a Nonresident Fellow at Resources for the Future.

STAFF

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California, Santa Barbara, she received her M.S. in biological oceanography from the College of Oceanic and Atmospheric Sciences at Oregon State University. Her master's degree research focused on how chemical and physical parameters in the surface ocean affect Antarctic phytoplankton species composition and consequently impact biogeochemical cycles. She obtained her Ph.D. in marine sciences from the University of California, Santa Barbara, where she conducted research on the photophysiology of harmful algal species. She joined the full-time staff of the National Academies' Board on Atmospheric Sciences and Climate in fall 2005, following a fellowship with the same group in winter 2005. She has been with the Ocean Studies Board since 2008. While with the Academies, she has worked on studies including the *Analysis of Global Change Assessments* (2007), *Strategic Guidance for the NSF's Support of Atmospheric Sciences* (2007), *Earth Observations from Space: The First 50 Years of Scientific Achievements* (2007), *Tsunami Warning and Preparedness* (2010), and *Adapting to the Impacts of Climate Change* (2010).

Jessica Dutton received her B.A. from Mount Holyoke College, and her Ph.D. in marine biology from the University of California, Santa Barbara. As an ecological physiologist, her doctoral research focused on understanding the relationship between species tolerances and coastal environmental conditions, and how such patterns relate to range distributions and climate change. She was a fellow in 2009 with the National Sea Grant Knauss Marine Policy Fellowship Program, and in 2012 with the Christine Mirzayan Science and Technology Policy Fellowship Program at the National Academy of Sciences. In the latter position, and subsequently as a research associate, she has worked with the Ocean Studies Board on several NRC studies including the "Effects of the Deepwater Horizon Mississippi Canyon-252 Oil Spill on Ecosystem Services in the Gulf of Mexico," "Review of the National Ocean Acidification Research Plan," and "Evaluating the Effectiveness of Stock Rebuilding Plans of the 2006 Fishery Conservation and Management Reauthorization Act."

Heather Chiarello joined the U.S. National Academy of Sciences in July 2008. She graduated magna cum laude from Central Michigan University in 2007 with a B.S. in political science with a concentration in public administration. Ms. Chiarello is currently a senior program assistant with the Ocean Studies Board in the Division on Earth and Life Sciences, and also with the Committee on International Security and Arms Control in the Policy and Global Affairs Division of the National Academies. She is pursuing a Master's degree in sociology and public policy analysis at The Catholic University of America in Washington, D.C.

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APPENDIX C

Acronyms and Terminology

ACRONYMS

ACT	NOAA Alliance for Coastal Technologies
BOEM	Bureau of Ocean Energy Management
CLIVAR	Climate Variability and Predictability Program
CO_2	Carbon dioxide
CCSP	Climate Change Science Program Strategic Plan
DOC	Dissolved organic carbon
DOS	Department of State
EPA	Environmental Protection Agency
FOARAM	Federal Ocean Acidification Research And Monitoring Act
FOCE	Free Ocean CO_2 Experiments
GDP	Gross domestic product
GLOBEC	Global Ocean Ecosystem Dynamics Program
GPRA	Government Performance and Results Act
IWGOA	Interagency Working Group on Ocean Acidification

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JGOFS	U.S. Joint Global Ocean Flux Study Program
LTER	Long Term Ecological Research
MPAs	Marine Protected Areas
NASA	National Aeronautics and Space Administration
NGO	Non-governmental Organization
NOAA	National Oceanic and Atmospheric Administration
NOPP	The National Oceanographic Partnership Program
NPO	National Ocean Acidification Program Office
NRC	National Research Council
NSF	National Science Foundation
NSTC	National Science and Technology Council
OCMIP	Ocean Carbon-Cycle Model Intercomparison Project
OMB	Office of Management and Budget
OSTP	Office of Science and Technology Policy
PIC	Particulate inorganic carbon
POC	Particulate organic carbon
SBIR	Federal Small Business Innovation Research Program
SOST	Subcommittee on Ocean Science and Technology
USFWS	U.S. Fish and Wildlife Service
USGCRP	U.S. Global Change Research Program
USGS	U.S. Geological Survey

TERMINOLOGY

As mentioned in Chapter 2, it is essential that attention be given to the choice and use of terminology. Some of the most fundamental terminology used in the field of ocean acidification can be confusing and lead to improper conclusions. Of particular importance are the terms used to discuss fundamental acid-base relationships. For example, great care is needed to employ acid-base terminology appropriately and, as discussed in Theme 6; an effort should be made to explain this terminology to non-scientists in a way that provides an accurate image of the processes and mechanisms of ocean acidification. The terms "acid" and "acidic" have specific chemical meaning. A reduction in pH does not necessarily mean that the solution in question, e.g., seawater, has in fact become acidic (i.e.,

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greater concentration of protons (H^+) than hydroxide ion). These terms may best be reserved for those exceptional conditions where seawater can actually become acidic (at CO_2 vents or in manipulation experiments). Similarly, the term 'alkalinity' is best replaced with 'total alkalinity' and explained for nonscientific audiences. Another term that is often used ambiguously due to its different meanings in different disciplines is *adaptation*. Whenever this term is used, it is essential to be explicit whether adaptation refers to biological adaptation or to human efforts to adapt to ocean acidification (e.g., through infrastructure or policy changes). In addition, 'mitigation' in the context of climate change refers to limiting carbon dioxide emissions. Thus, the Strategic Plan could be improved by using the term 'mitigation' or 'to mitigate' only in the context of lowering carbon dioxide emissions and not in the context of decreasing the impacts of ocean acidification. In that context, 'adaptation' is the more appropriate term as it refers to human interventions through changes in infrastructure or management of the marine resources. In Theme 2 terms such as 'keystone species,' 'bellwether species,' 'indicator species' are used seemingly interchangeable, despite the fact that 'keystone species' and 'indicator species' do not refer to the same concept. The inconsistent use of these terms needs to be reviewed in Theme 2 and confusion can be minimized by using terms more consistently with their original definitions. Given these issues, the committee offers the following definitions for the purpose of this report and suggest versions of these definitions be provided in the Strategic Plan:

> Adaptation: "Adjustment in natural or human systems to a new or changing environment that exploits beneficial opportunities or moderates negative effects" (NRC, 2010).

> Hydrogen Ion Concentration: "The hydrogen ion concentration in seawater is reported as $pH=-lg[H^+]$" (Riebesell et al., 2010).

> Indicator Species: "A species whose presence, absence, or relative well-being in a given environment is a sign of the overall health of its ecosystem. By monitoring the condition and behavior of an indicator species, scientists can determine how changes in the environment are likely to affect other species that are more difficult to study."[1]

[1] Indicator species. Dictionary.com. The American Heritage® Science Dictionary. Houghton Mifflin Company. http://dictionary.reference.com/browse/indicator species (accessed: December 14, 2012).

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Total Alkalinity: "The total alkalinity of a sea water sample is defined as the number of moles of hydrogen ion equivalent to the excess of proton acceptors (bases formed from weak acids with a dissociation constant K ≤ 10–4.5 at 25°C and zero ionic strength) over proton donors (acids with K > 10–4.5) in 1 kilogram of sample" (Dickson, 1981).

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