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Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean

Committee on the Development of an Integrated Science Strategy for Ocean Acidification Monitoring, Research, and Impacts Assessment; National Research Council

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The ocean has absorbed a significant portion of all human-made carbon dioxide emissions. This benefits human society by moderating the rate of climate change, but also causes unprecedented changes to ocean chemistry. Carbon dioxide taken up by the ocean decreases the pH of the water and leads to a suite of chemical changes collectively known as ocean acidification. The long term consequences of ocean acidification are not known, but are expected to result in changes to many ecosystems and the services they provide to society. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean reviews the current state of knowledge, explores gaps in understanding, and identifies several key findings. Like climate change, ocean acidification is a growing global problem that will intensify with continued CO2 emissions and has the potential to change marine ecosystems and affect benefits to society. The federal government has taken positive initial steps by developing a national ocean acidification program, but more information is needed to fully understand and address the threat that ocean acidification may pose to marine ecosystems and the services they provide. In addition, a global observation network of chemical and biological sensors is needed to monitor changes in ocean conditions attributable to acidification.

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SUMMARY

The ocean absorbs a significant portion of carbon dioxide (CO_2) emissions from human activities, equivalent to about one-third of the total emissions for the past 200 years from fossil fuel combustion, cement production and land use change (Sabine et al., 2004). Uptake of CO_2 by the ocean benefits society by moderating the rate of climate change but also causes unprecedented changes to ocean chemistry, decreasing the pH of the water and leading to a suite of chemical changes collectively known as ocean acidification. Like climate change, ocean acidification is a growing global problem that will intensify with continued CO_2 emissions and has the potential to change marine ecosystems and affect benefits to society.

The average pH of ocean surface waters has decreased by about 0.1 unit—from about 8.2 to 8.1—since the beginning of the industrial revolution, with model projections showing an additional 0.2-0.3 drop by the end of the century, even under optimistic scenarios (Caldeira and Wickett, 2005).[1] Perhaps more important is that the rate of this change exceeds any known change in ocean chemistry for at least 800,000 years (Ridgewell and Zeebe, 2005). The major changes in ocean chemistry caused by increasing atmospheric CO_2 are well understood and can be precisely calculated, despite some uncertainty resulting from biological feedback processes. However, the direct biological effects of ocean acidification are less certain and will vary among organisms, with some coping well and others not at all. The long term consequences of ocean acidification for marine biota are unknown, but changes in many ecosystems and the services they provide to society appear likely based on current understanding (Raven et al., 2005).

In response to these concerns, Congress requested that the National Research Council conduct a study on ocean acidification in the Magnuson-Stevens Fishery Conservation and Management Reauthorization Act of 2006. The *Committee on the Development of an Integrated Science Strategy for Ocean Acidification Monitoring, Research, and Impacts Assessment* is charged with reviewing the current state of knowledge and identifying key gaps in information to help federal agencies develop a program to improve understanding and address the consequences of ocean acidification (see Box S.1 for full statement of task). Shortly after the study was underway, Congress passed another law—the Federal Ocean Acidification Research and Monitoring (FOARAM) Act of 2009—which calls for, among other things, the establishment of a federal ocean acidification program; this report is directed to the ongoing strategic planning process for such a program.

Box S.1
Statement of Task

Among the many potential direct and indirect impacts of greenhouse gas emissions (particularly CO_2) and global warming, this study will examine the anticipated consequences of ocean acidification due to rising atmospheric carbon dioxide levels on fisheries, protected species, coral reefs, and other natural resources in the United States and internationally. The committee will recommend priorities for a national research, monitoring, and assessment plan to advance understanding of the biogeochemistry of carbon dioxide uptake in the ocean and the relationship to atmospheric levels of carbon dioxide, and to reduce uncertainties in projections of

[1] "Acidification" does not mean that the ocean has a pH below neutrality. The average pH of the ocean is still basic (8.1), but because the pH is decreasing, it is described as undergoing acidification.

increasing ocean acidification and the potential effects on living marine resources and ocean ecosystems. The committee's report will:

1. Review current knowledge of ocean acidification, covering past, present, and anticipated future effects on ocean ecosystems.
    A. To what degree is the present understanding sufficient to guide federal and state agencies in evaluating potential impacts for environmental and living resource management?
    B. To what degree are federal agency programs and plans responsive to the nation's needs for ocean acidification research, monitoring and assessments?

2. Identify critical uncertainties and key science questions regarding the progression and impacts of ocean acidification and the new information needed to facilitate research and decision making for potential mitigation and adaptation options.
    A. What are the critical information requirements for impact assessments and forecasts (e.g., biogeochemical processes regulating atmospheric CO_2 exchange, buffering, and acidification; effects of acidification on organisms at various life stages and on biomineralization; and the effects of parallel stressors)?
    B. What should be the priorities for research and monitoring to provide the necessary information for national and regional impact assessments for living marine resources and ocean ecosystems over the next decade?
    C. How should the adverse impacts of ocean acidification be measured and valued?
    D. How could additional research and modeling improve contingency planning for adaptive management of acidification impacts on marine ecosystems and resources?

3. Recommend a strategy of research, monitoring, and assessment for federal agencies, the scientific community, and other partners, including a strategy for developing a comprehensive, coordinated interagency program to address the high priority information needs.
    A. What linkages with states, non-governmental organizations, and the international science community are required?
    B. What is the appropriate balance among (a) short and long term research goals and (b) research, observations, modeling, and communication?
    C. What opportunities are available to collaborate with international programs, such as the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) and Surface Ocean – Lower Atmosphere Study (SOLAS) projects, and non-U.S. programs, such as the European Project on Ocean Acidification (EPOCA)? What would be the value of coordinating U.S. efforts through international scientific organizations such as the Intergovernmental Oceanographic Commission (IOC), the International Council for Science Scientific Committee on Oceanic Research (SCOR), the World Climate Research Programme (WCRP), the International Council for the Exploration of the Sea (ICES), and the North Pacific Marine Science Organization (PICES)?

Although ocean acidification research is in its infancy, there is already growing evidence of changes in ocean chemistry and ensuing biological impacts. Time-series measurements and other field data have documented the decrease in ocean pH and other related changes in seawater chemistry (Dore et al., 2009). The absorption of anthropogenic CO_2 by the oceans increases the concentration of hydrogen ions in seawater (quantified as a decrease in pH), and also brings increases in CO_2 and bicarbonate ion concentrations and decreases the carbonate ion concentration. These changes in the inorganic carbon and acid-base chemistry of seawater can affect physiological processes in marine organisms such as carbon fixation in photosynthesis, maintenance of physiological pH in internal fluids and tissues, or precipitation of carbonate minerals. Some of the strongest evidence of the potential impacts of ocean acidification on marine ecosystems comes from experiments on calcifying organisms; acidifying seawater to various extents has been shown to affect the formation and dissolution of calcium carbonate shells and skeletons in a range of marine organisms including reef-building corals, commercially-important mollusks such as oysters and mussels, and many phytoplankton and zooplankton species that form the base of marine food webs.

It is important to note that the concentration of atmospheric CO_2 is rising too rapidly for natural, $CaCO_3$-cycle processes to maintain the pH of the ocean. As a consequence, the average pH of the ocean will continue to decrease as the surface ocean absorbs more atmospheric CO_2. In contrast, atmospheric CO_2 increased over thousands of years during the glacial/interglacial cycles of the past 800,000 years, slow enough for the $CaCO_3$ cycle to compensate and maintain near constant pH (Hönisch et al., 2009). In the deeper geologic past—many millions of years ago—atmospheric CO_2 reached levels multiple times higher than present conditions, resulting in a tropical climate up to the high latitudes. The similarity of these deep past events to the current anthropogenic increase in atmospheric CO_2 is unclear because the timeframes for CO_2 release are not well constrained. If CO_2 levels increased over thousands of years during these deep past events, the $CaCO_3$ cycle would have stabilized the ocean against changes in pH (Caldeira et al., 1999). Better reconstructions of the time frame of those hot house/ice house CO_2 perturbations and the environmental conditions that ensued will be necessary to determine whether the changes in marine ecosystems observed in the fossil record reflect an increased acidification of the paleo-ocean during that time.

Experimental reduction of seawater pH with CO_2 affects many biological processes, including calcification, photosynthesis, nutrient acquisition, growth, reproduction, and survival, depending upon the amount of acidification and the species tested (Orr et al., 2009). It is currently not known if and how various marine organisms will ultimately acclimate or adapt to the chemical changes resulting from acidification, but existing data suggest that there likely will be ecological winners and losers, leading to shifts in the composition and functioning of many marine ecosystems. It is also not known how these changes will interact with other environmental stressors such as climate change, overfishing, and pollution. Most importantly, despite the potential for socioeconomic impacts to occur in coral reef systems, aquaculture, fisheries, and other sectors, there is not currently enough information to assess these impacts, much less develop plans to mitigate or adapt to them.

CONCLUSION: The chemistry of the ocean is changing at an unprecedented rate and magnitude due to anthropogenic carbon dioxide emissions; the rate of change exceeds any known to have occurred for at least the past hundreds of thousands of years.
Unless anthropogenic CO_2 emissions are substantially curbed, or atmospheric CO_2 is controlled by some other means, the average pH of the ocean will continue to fall. Ocean acidification has demonstrated impacts on many marine organisms. While the ultimate

consequences are still unknown, there is a risk of ecosystem changes that threaten coral reefs, fisheries, protected species, and other natural resources of value to society.

CONCLUSION: Given that ocean acidification is an emerging field of research, the committee finds that the federal government has taken initial steps to respond to the nation's long-term needs and that the national ocean acidification program currently in development is a positive move toward coordinating these efforts.

An ocean acidification program will require coordination at the international, national, regional, state, and local levels. Within the U.S. federal government, it will involve many of the greater than 20 agencies that are engaged in ocean science and resource management. To address the full scope of potential impacts, strong interactions among scientists in multiple fields and from various organizations will be required and two-way communication with stakeholders will be necessary. Ultimately, a successful program will have an approach that integrates basic science with decision support.

The growing concern over ocean acidification is demonstrated in the several workshops that have been convened on the subject, as well as scientific reviews and community statements (e.g., Raven et al., 2005; Doney et al., 2009; Kleypas et al., 2006; Fabry et al., 2008a; Orr et al., 2009; European Science Foundation, 2009). These reviews and reports present a community-based statement on the science of ocean acidification as well as steps needed to better understand and address it; they provide the groundwork for the committee's analysis.

CONCLUSION: The development of a National Ocean Acidification Program will be a complex undertaking, but legislation has laid the foundation, and a path forward has been articulated in numerous reports that provide a strong basis for identifying future needs and priorities for understanding and responding to ocean acidification.

The committee's recommendations, presented below, include six key elements of a successful national ocean acidification program: (1) a robust observing network, (2) research to fulfill critical information needs, (3) assessments and support to provide relevant information to decision makers, (4) data management, (5) facilities and training of ocean acidification researchers, and (6) effective program planning and management.

OBSERVING NETWORK

Many publications have noted the critical need for long-term monitoring of ocean and climate to document and quantify changes, including ocean acidification, and that the current observation systems for monitoring these changes are insufficient. A global network of robust and sustained chemical and biological observations will be necessary to establish a baseline and to detect and predict changes attributable to acidification.

The first step in developing the observing network will be identification of the appropriate chemical and biological parameters to be measured by the network and ensuring data quality and consistency across space and time. There is widespread agreement on the chemical parameters (and methods and tools for measurement) for monitoring ocean acidification. Unlike the chemical parameters, there are no agreed upon metrics for biological variables. In part, this is because the field is young and in part because the biological effects of ocean acidification, from the cellular to the ecosystem level, are very complex. To account for this complexity, the program will need to monitor parameters that cover a range of organisms and ecosystems and support both laboratory-based and field research. The development of new tools and techniques, including novel autonomous sensors, would greatly improve the ability to make relevant chemical and biological measurements over space and time and will be necessary to identify and characterize essential biological indicators concerning the ecosystem consequences of ocean acidification. As critical biological indicators and metrics are identified, the Program will need to incorporate those measurements into the research plan, and thus, adaptability in response to developments in the field is a critical element of the monitoring program.

The next step in developing the observing network will be consideration of available resources. A number of existing sites and surveys could serve as a backbone for an ocean acidification observational network, but these existing sites were not designed to observe ocean acidification and thus do not provide adequate coverage or measurements of key parameters. The current system of observations would be improved by adding sites and measurements in ecosystems projected to be vulnerable to ocean acidification (e.g., coral reefs and polar regions) and areas of high variability (e.g., coastal regions). Two community-based reports (Fabry et al., 2008a; Feely et al., 2010) identify vulnerable ecosystems, measurement requirements, and other details for developing an ocean acidification observational network. Another important consideration is the sustainability of long-term observations, which remains a perpetual challenge but is critical given the gradual, cumulative, and long-lasting pressure of ocean acidification. Integrating the network of ocean acidification observations with other ocean observing systems will help to ensure sustainability of the acidification-specific observations.

CONCLUSION: The chemical parameters that should be measured as part of an ocean acidification observational network and the methods to make those measurements are well-established.

RECOMMENDATION: The National Program should support a chemical monitoring program that includes measurements of temperature, salinity, oxygen, nutrients critical to primary production, and at least two of the following four carbon parameters: dissolved inorganic carbon, pCO_2, total alkalinity, and pH. To account for variability in these values with depth, measurements should be made not just in the surface layer, but with consideration for different depth zones of interest, such as the deep sea, the oxygen minimum zone, or in coastal areas that experience periodic or seasonal hypoxia.

CONCLUSION: Standardized, appropriate parameters for monitoring the biological effects of ocean acidification cannot be determined until more is known concerning the physiological responses and population consequences of ocean acidification across a wide range of taxa.

RECOMMENDATION: To incorporate findings from future research, the National Program should support an adaptive monitoring program to identify biological response variables specific to ocean acidification. In the meantime, measurements of general indicators of ecosystem change, such as primary productivity, should be supported as part of a program for assessing the effects of acidification. These measurements will also have value in assessing the effects of other long-term environmental stressors.

RECOMMENDATION: To ensure long-term continuity of data sets across investigators, locations, and time, the National Ocean Acidification Program should support inter-calibration, standards development, and efforts to make methods of acquiring chemical and biological data clear and consistent. The Program should support the development of satellite, ship-based, and autonomous sensors, as well as other methods and technologies, as part of a network for observing ocean acidification and its impacts. As the field advances and a consensus emerges, the Program should support the identification and standardization of biological parameters for monitoring ocean acidification and its effects.

CONCLUSION: The existing observing networks are inadequate for the task of monitoring ocean acidification and its effects. However, these networks can be used as the backbone of a broader monitoring network.

RECOMMENDATION: The National Ocean Acidification Program should review existing and emergent observing networks to identify existing measurements, chemical and biological, that could become part of a comprehensive ocean acidification observing network and to identify any critical spatial or temporal gaps in the current capacity to monitor ocean acidification. The Program should work to fill these gaps by:

- **ensuring that existing coastal and oceanic carbon observing sites adequately measure the seawater carbonate system and a range of biological parameters;**
- **identifying and leveraging other long-term ocean monitoring programs by adding relevant chemical and biological measurements at existing and new sites;**
- **adding additional time-series sites, repeat transects, and in situ sensors in key areas that are currently undersampled. These should be prioritized based on ecological and societal vulnerabilities.**
- **deploying and field testing new remote sensing and in situ technologies for observing ocean acidification and its impacts; and**
- **supporting the development and application of new data analysis and modeling techniques for integrating satellite, ship-based, and in situ observations.**

RECOMMENDATION: The National Ocean Acidification Program should plan for the long-term sustainability of an integrated ocean acidification observation network.

RESEARCH PRIORITIES

Ocean acidification research is still in its infancy. A great deal of research has been conducted and new information gathered in the past several years, and it is clear from this research that ocean acidification may threaten marine ecosystems and the services they provide. However, much more information is needed in order to fully understand and address these changes. Most previous research on the biological effects of ocean acidification has dealt with acute responses in a few species, and very little is known about the impacts of acidification on many ecologically or economically important organisms, their populations, and communities; the effects on a variety of physiological and biogeochemical processes; and the capacity of organisms to adapt to projected changes in ocean chemistry (Boyd et al., 2008). There is a need for research that provides a mechanistic understanding of physiological effects, elucidates the acclimation and adaptation potential of organisms, and allows scaling up to ecosystem effects, taking into account the role and response of humans in those systems and how best to support decision making in affected systems. There is also a need to understand these effects in light of multiple and potentially compounding environmental stressors, such as increasing temperature, pollution, and overfishing. The committee identifies eight broad research areas that address these critical information gaps; detailed research recommendations on specific regions and topics are contained in other community-based reports (i.e., Raven et al., 2005; Kleypas et al., 2006; Fabry et al., 2008a; Orr et al., 2009; Joint et al., 2009).

CONCLUSION: Present knowledge is insufficient to guide federal and state agencies in evaluating potential impacts for management purposes.

RECOMMENDATION: Federal and federally-funded research on ocean acidification should focus on the following eight unranked priorities:

- **understand processes affecting acidification in coastal waters;**
- **understand the physiological mechanisms of biological responses;**
- **assess the potential for acclimation and adaptation;**
- **investigate the response of individuals, populations, and communities;**
- **understand ecosystem-level consequences;**
- **investigate the interactive effects of multiple stressors;**
- **understand the implications for biogeochemical cycles; and**
- **understand the socioeconomic impacts and inform decisions.**

ASSESSMENT AND DECISION SUPPORT

The FOARAM Act of 2009 charges an interagency working group with overseeing the development of impacts assessments and adaptation and mitigation strategies, and with facilitating communication and outreach with stakeholders. Because ocean acidification is a relatively new concern and research results are just emerging, it will be challenging to move from science to decision support. Nonetheless, ocean acidification is occurring now and will continue for some time. Resource managers will need information in order to adapt to changes in ocean chemistry and biology. In view of the limited current knowledge about the impacts of ocean acidification, the first step for the National Ocean Acidification Program will be to clearly define the problem and the stakeholders (i.e., for whom is this a problem and at what time scales), and build a process for decision support. It must be noted that a one-time identification of stakeholders and their concerns will not be adequate in the long term, and it should be considered an iterative process. As research is performed and the effects of ocean acidification are better defined, additional stakeholders may be identified, and the results of the socioeconomic analysis may change. For climate change decision support, there have been pilot programs within some federal agencies and there is growing interest within the federal government for developing a national climate service to further develop climate-related decision support. Similarly, new approaches for ecosystem-based management and marine spatial planning are also being developed. The National Ocean Acidification Program could leverage the expertise of these existing and future programs.

RECOMMENDATION: The National Ocean Acidification Program should focus on identifying, engaging, and responding to stakeholders in its assessment and decision support process and work with existing climate service and marine ecosystem management programs to develop a broad strategy for decision support.

DATA MANAGEMENT

Data quality and access, as well as appropriate standards for data reporting and archiving, will be integral components of a successful program to enhance the value of data collected and ensure they are accessible (with appropriate metadata) to researchers now and in the future. Other large-scale research programs have developed data policies that address data quality, access, and archiving to enhance the value of data collected within these programs, and the research community has developed *The Guide to Best Practices in Ocean Acidification Research and Data Reporting* to provide guidance on data reporting and usage (Riebesell et al., 2010). A successful program will require a management office with sufficient resources to guide data management and synthesis, development of policies, and communication with principal investigators. There are many existing data management offices and databases that could support ocean acidification observational and research data.

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

RECOMMENDATION: The National Ocean Acidification Program should create a data management office and provide it with adequate resources. Guided by experiences from previous and current large-scale research programs and the research community, the office should develop policies to ensure data and metadata quality, access, and archiving. The Program should identify appropriate data center(s) for archiving of ocean acidification data or, if existing data centers are inadequate, the Program should create its own.

RECOMMENDATION: In addition to management of research and observational data, the National Ocean Acidification Program, in establishing an Ocean Acidification Information Exchange, should provide timely research results, syntheses, and assessments that are of value to managers, policy makers, and the general public. The Program should develop a strategy and provide adequate resources for communication efforts.

FACILITIES AND HUMAN RESOURCES

Facilities and trained researchers will be needed to achieve the research priorities and observations described in this document. This may include large community resources and facilities including, for example, central facilities for high-quality carbonate chemistry measurements or technically complex experimental systems (e.g., free-ocean CO_2 experiment (FOCE)-type sites, mesocosms), facilities located at sites with natural pH gradients and variability, or intercomparison studies to enable integration of data from different investigators.

There are some community facilities of this scale, but they are currently quite limited. Large facilities may be required to scale up to ecosystem-level experiments, although there are scientific and economic trade-offs among the various types of facilities.

Similarly, ocean acidification is a highly interdisciplinary and growing field that is attracting new graduate students, post-doctoral investigators, and principal investigators. Training opportunities to help scientists make the transition to this new field, and to engage researchers in fields related to management and decision support, will accelerate the progress in ocean acidification research.

RECOMMENDATION: As the National Ocean Acidification Program develops a research plan, the facilities and human resource needs should also be assessed. Existing community facilities available to support high-quality field- and laboratory-based carbonate chemistry measurements, well-controlled carbonate chemistry manipulations, and large-scale ecosystem manipulations and comparisons should be inventoried and gaps assessed based on research needs. An assessment should also be made of community data resources such as genome sequences for organisms vulnerable to ocean acidification. Where facilities or data resources are lacking, the Program should support their development, which in some cases also may require additional investments in technology development. The Program should also support the development of human resources through workshops, short-courses, or other training opportunities.

PROGRAM PLANNING, STRUCTURE, AND MANAGEMENT

The committee delineates ambitious priorities and goals for the National Ocean Acidification Program. The FOARAM Act calls for the development of a detailed, 10-year strategic plan for the National Ocean Acidification Program; while the ultimate details of such a plan are outside the scope of this report, the Program will need to lay out a clear strategic plan to identify key goals and set priorities, as well as a detailed implementation plan. Community input into plan development will promote transparency and community acceptance of the plans and Program. A 10-year plan allows for planned evaluations: in addition to a final 10-year assessment of the program, a mid-term review after 5 years would be useful in evaluating the progress toward the goals and making appropriate corrections. While the 10-year period outlined in the FOARAM Act may be adequate to achieve some goals, it is likely that the Program in its entirety will extend beyond this initial timeframe and some operational elements may continue indefinitely. During the initial 10-year period, a legacy program for extended time series measurements, research, and management will need to be developed. The committee identifies eight key elements that will need to be included in the strategic plan (see below).

If fully executed, the elements outlined in the FOARAM Act and recommended in this report would create a large and complex program that will require sufficient support. These program goals are certainly on the order of, if not more ambitious than, previous major oceanographic programs and will require a high level of coordination that warrants a program office to coordinate the activities of the program and serve as a central point for communicating and collaborating with outside groups such as Congress and international ocean acidification programs. International collaboration is critical to the success of the Program; ocean acidification is a global problem which requires a multinational research approach. Such collaboration also affords opportunities to share resources (including expensive large-scale facilities for ecosystem-level manipulation) and expertise that may be beyond the capacity of one single nation.

RECOMMENDATION: The National Ocean Acidification Program should create a detailed implementation plan with community input. The plan should address (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) agency roles and responsibilities; (6) coordination with existing and developing national and international programs; (7) resource requirements; and (8) community input and external review.

RECOMMENDATION: The National Ocean Acidification Program should create a program office with the resources to ensure successful coordination and integration of all of the elements outlined in the FOARAM Act and this report.

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Ocean Acidification:
A National Strategy to Meet the Challenges of a Changing Ocean

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Committee on the Development of an Integrated Science Strategy for Ocean Acidification Monitoring, Research, and Impacts Assessment

Ocean Studies Board

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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:

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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 **Kenneth H. Brink**, Woods Hole Oceanographic Institution, appointed by the Divison on Earth and Life Studies, and **W. L. Chameides**, Duke University, appointed by the Report Review Committee, who were 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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